

# **An ERP Investigation of Response-related Processes**

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## **Abstract**

Several ERP correlates of response-monitoring have been investigated over the past two decades, with a number of competing theories emerging. Models of early negative components focus on explanations involving a comparative process between error and correct responses or a reinforcement-learning process. These theories are representative of either a specific error-processing or a generic response-monitoring system. These models provide some structure to explain experimental outcomes, but fail to account for much evidence, particularly in terms of individual differences in goal-directed behaviour, response awareness and task-specific factors that may impact the overall evaluation of action and intention. Whereas some research evidence has indicated a clear and functional separation of early and later response-related components, other researchers have found associations where both early and later components are impacted by prevailing experimental conditions. Thus the overarching aim of this thesis was to investigate the impact of task difficulty, conscientiousness, task and response salience, response awareness and task-specific factors on both early and late, error and correct response-related ERP components.

Experiment 1 focused on investigating task demands, response awareness and conscientiousness in terms of ERN/Ne, CRN, early and late Pe and corresponding Pc mean amplitudes, in a standard arrowhead two-choice flanker task. Overall errors were found to elicit larger mean amplitude than correct responses. No effects of response awareness were evident at any stage of the response evaluation process, however as this outcome was based on small sample sizes interpretation was approached cautiously. Conscientiousness was found to differentiate component amplitudes in terms of task difficulty, particularly for error-related components.

Overall, results suggest that individual differences in terms of underlying personality traits may play a role in the evaluation of errors.

Experiment 2 was designed to consider task difficulty in terms of overall response-monitoring using a four-choice flanker task. Response awareness and conscientiousness were also investigated. Again, analysis of early error and correct related components revealed significant amplitude differences. While early components also showed effects of response awareness this was based on very small sample sizes and as such did not provide a basis for a definitive interpretation. Similar to the outcomes of Experiment 1, differentiation of component amplitudes was apparent in terms of conscientiousness and task difficulty; however, in this instance this was only associated with correct response-related components.

Experiment 3 aimed to examine the impact of task salience, conscientiousness and response awareness on response-related ERP components in a more complex language based task. Since ability to decode non-words was fundamental to the completion of the task, decoding ability was also included in the overall design and analyses. The initial analysis of this data including decoding ability and task salience revealed no significant differences in ERN/Ne and CRN mean amplitude indicating that response-related components may be impacted by task difficulty or stimulus discriminability. However, when further analyses were completed including conscientiousness, response awareness, and left and right coronal measures a differing picture began to emerge. Early negativities were found to be impacted by conscientiousness suggesting individual differences in goal directed behaviour should be considered in overall explanations of response- and error-monitoring processes. Clear coronal differences in late components indicated differential hemispheric processing in response evaluation. Since stimulus evaluation processes

were also evidenced in differences in hemispheric activity, this outcome points to an explanation involving the specific nature of the phonological decoding task.

Taken together, the findings of this series of experiments suggest that task-specific factors including task difficulty play a role in overall response evaluation processes, but that this also takes place within the context of individual personality differences. Furthermore, the evidence suggests that all response-related ERP components, early and late, error and correct, may combine to offer a fuller explanation of response-monitoring.

# Chapter 1

## Overview of Thesis

Monitoring and evaluating performance provide information necessary for adaptive behaviour and are essential components of human information processing systems. Since the first reports of response-locked early negative event-related potential (ERP) components that were associated with erroneous responses (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1990, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993), the investigation of response monitoring has grown considerably. This burgeoning area of research has contributed to the development of various theories that attempt to explain not only early negative, but also early positive and late positive, components, all associated with processing and evaluation of information associated with responses. In the main, current theories focus on a comparative process: highlighting an evaluation of correct and error responses at some point in the progression of information processing associated with response monitoring. Whereas some researchers argue for a generic response monitoring process (Falkenstein et al., 1990, 1991; Suchan, Jokisch, Skotara, & Daum, 2007), others propose a distinct error monitoring system (Holroyd & Coles, 2002). Many studies reported in the literature consider some representative components of response monitoring in isolation (e.g., Dikman & Allen, 2000; Hogan, Vargha-Khadem, Kirkham, & Baldeweg, 2005; Masaki, Falkenstein, Stürmer, Pinkpank, & Sommer, 2007), or the functional separation of some error-related components only (e.g., Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Leuthold & Sommer, 1999; Mathewson, Dywan, & Segalowitz, 2005; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001). To date, only a small number of studies have considered all error and correct response-related components and the impact of prevailing

experimental conditions. Thus, in an attempt to more clearly explicate the nature of response-related processes, the primary aim of this thesis is to consider all response-related ERP components in terms of their antecedent conditions.

This introductory chapter provides a synopsis of the structure of this thesis and is followed by a chapter reviewing the theories proposed to explain the electrophysiological changes that are associated with error and correct responses (ERN/Ne, CRN, early and late Pe and Pc). An overview of the mismatch hypothesis (Falkenstein et al., 1990, 1991), the reinforcement-learning hypothesis (Holroyd & Coles, 2002), and the conflict monitoring hypothesis (Yeung, Botvinick, & Cohen, 2004) of response-monitoring and error detection are provided in the first subsections of Chapter 2. These are followed by an outline of specific explanations of correct response negativity (CRN) (Ford, 1999; Vidal, Hasbroucq, Grapperon, & Bonnet, 2000). Further subsections of Chapter 2 describe an early and late error positivity (Pe) and provide an overview of differing accounts of this error-related ERP component; conscious error recognition (Falkenstein, 2004a; Nieuwenhuis et al., 2001; Shalgi, Barkan, & Deouell, 2009), response strategy updating (Hajcak, MacDonald, & Simons, 2003; Nieuwenhuis et al., 2001), emotional error processing (Falkenstein et al., 2000; Herrmann, Römmler, Ehlis, Heidrich, & Fallgatter, 2004), and the similarity in function to that of P3b (Falkenstein et al., 1991; Leuthold & Sommer, 1999; Overbeek, Nieuwenhuis, & Ridderinkhof, 2005; Ridderinkhof, Ramautar, & Wijnen, 2009). An overview of the content of current literature focusing on correct response positivity (Pc) is then discussed (Burgio-Murphy et al., 2007; Kim et al., 2006; Mathalon et al., 2002). This chapter concludes with a summary highlighting the incomplete picture provided by present literature and

suggests that current theories do not yet provide a unified explanation of response-related activity.

Chapter 3 provides a review of research evidence outlining the factors impacting response-related ERP components. The first subsection covers task difficulty and its impact on ERN/Ne, CRN and Pe. This section, while highlighting the need to extend research beyond typical experimental paradigms, also discusses evidence that response-related components may reflect task demands (e.g., Falkenstein, 2004a; Hogan et al., 2005; Masaki et al., 2007). Chapter 3 then provides a discussion of individual differences in terms of conscientiousness and how experimental evidence suggests conscientiousness may modulate the perceived importance of tasks and responses, and be reflected in response-related amplitude differences (Pailing & Segalowitz, 2004a). This is followed by an overview of further research that has provided support for the argument that response-related component amplitudes may be moderated by task and response salience (e.g., Gehring et al., 1993; Hajcak, Moser, Yeung, & Simons, 2005). The following subsection of Chapter 3 focuses on response awareness and perceptions of response accuracy in terms of modulators of response-related component activity. Review of this material has highlighted a growing body of evidence indicating early and late response-related components, both error and correct, may be modified according to an individual's awareness of their responses (e.g., Endrass, Franke, & Kathmann, 2005; Endrass, Reuter, & Kathmann, 2007; Nieuwenhuis et al., 2001; Shalgi et al., 2009; Scheffers, & Coles, 2000). The next subsection of Chapter 3 draws attention to the fact that some researchers investigating response-related processes have argued that explanations attributed to developmental or psychopathological factors may also be explained by task-specific factors (e.g., Albrecht et al., 2008; Burgio-Murphy et al., 2007; Hajcak



& Simons, 2002; Liotti, Pliszka, Perez, Kothmann, & Woldorff, 2005; Mathewson et al., 2005; Ruchow et al., 2005). The use of language-based tasks to investigate response monitoring has also provided further evidence that task-specific factors play a distinct role in response monitoring processes (e.g., Ganushchak & Schiller, 2008; Horowitz-Kraus & Breznitz, 2008). In light of distinct explanations for ERN/Ne, CRN, Pe, and Pc, a summary of the ongoing investigations of the dissociability of these response-related components is presented. Chapter 3 concludes with a summary emphasising the complex interplay of factors that may impact response-related activity.

A variety of quantification methods have been used in terms of error-related components with inconsistencies noted in the literature that may be attributable to quantification choice (Overbeek et al., 2005). Consequently, a comparison of differing quantification methods of the ERN/Ne was undertaken. Since quantification method is not specific to the thesis topic, but informed the measurement of components of interest, an outline of this evaluation is provided in Appendix A.

Chapter 4 provides an overall rationale and outlines the general aim of each experiment. Chapter 5 provides the details of the first experiment, in a series of three, that investigated response-related processes, both error and correct, and their interplay with task demands, response awareness and conscientiousness within a two-alternate forced choice task paradigm. Chapter 6 reports details of Experiment 2. The aim of this study was to examine the effects of task demands using a more difficult four-alternate forced choice task along with response awareness and the impact of levels of conscientiousness on response-related processes. Details of the final experiment in the series are presented in Chapter 7. This experiment aimed to examine early and late response-related components in a more complex, language

based, reaction-time task. This thesis concludes with a general discussion and conclusion that suggests that response-related processes occur within, and are influenced by, a complex interaction of individual differences and task-specific factors (Chapter 8).

## **Chapter 2**

### **Response-related Components: Theories and Evidence**

#### **Error-Related Negativity/Error Negativity (ERN/Ne)**

Errors provide a crucial source of information in the regulation of cognitive processes involved with monitoring and evaluation of performance. In recent years researchers have proposed a neural basis for response monitoring and evaluation involving two event-related potential components. Initially, an early post error response negative deflection was identified as error negativity (Ne) (Falkenstein et al., 1990, 1991) and later referred to as error-related negativity (ERN) by Gehring et al. (1993). These differing terms were coined by the original researchers and continue to be variously noted in the literature, together with combinations of abbreviations (e.g., Ne/ERN or ERN/Ne); however it is agreed that they all represent the same component (Coles, Scheffers, & Holroyd, 2001). For the purpose of this thesis, this component will be referred to as ERN/Ne. The second ERP implicated in explanations of performance monitoring is error positivity (Pe) (Falkenstein et al., 1990, 1991). The ERN/Ne has occurred across a range of stimulus and response modalities and thus has been described as activity associated with a generic response-monitoring system (Falkenstein et al., 1991). This ERP is generally observed following errors as a fronto-central negative peak occurring between 50 and 100 ms post-response. Explanations involving error detection, reinforcement-learning and response-conflict provide the basis for several models or theories of the ERN/Ne.

## **Mismatch Hypothesis**

When Falkenstein et al. (1990) first described the ERN/Ne they argued that this component was the manifestation of the recognition of a mismatch between response options. That is, the ERN/Ne reflects an inconsistency that is detected between an actual, erroneous response and a required, correct response. The explanation of this as a 'response identification' process where stimuli are matched to an appropriate response has considerable empirical support.

Falkenstein et al. (1990) used a choice reaction time task to investigate the ERN/Ne and presented visual and auditory stimuli to participants in focused (only visual or auditory stimuli) and divided (random presentation of both visual and auditory stimuli) attention conditions. They argued that smaller amplitudes of the ERN/Ne component seen when participants made errors on reaction time tasks under extreme time pressure compared to those errors made under moderate time pressure may reflect an impaired representation of the correct, required response.

Scheffers and Coles (2000) examined performance monitoring using a letter version of the Erikson flanker task (Eriksen & Eriksen, 1974). They found that the amplitude of the ERN/Ne covaried with judgments of response accuracy; that is, sureness of responses was associated with larger ERN/Ne amplitudes and not uncertainty of responses. They argued that this difference suggests that a comparison between actual and required responses takes place and provides support for the mismatch hypothesis.

Falkenstein (2004a), drawing on evidence gathered from Gehring and Knight's (2000) study investigating the role of pre-frontal cortical areas in action monitoring, argued that the dorso-lateral pre-frontal cortex (DLPFC) plays a critical role in the formation of correct response representations. Gehring and Knight found that young

or aged-matched „normal’ participants demonstrated expected ERN/Ne amplitudes, with error responses producing larger negative amplitudes compared to correct responses when completing a speeded reaction time task. However, those participants with lateral prefrontal lesions produced component amplitudes that showed no difference across correct and incorrect responses, more specifically, correct response components were augmented for participants with prefrontal lesions compared to control participants. Falkenstein argues that the lack of amplitude difference between error and correct responses in lesion patients may be due to the inability to detect differences between response types and suggests that the DLPFC is instrumental in the production of correct response representations that act as comparators in the process of error detection. Accordingly, this evidence provides support for the efficacy of the mismatch hypothesis and also for the argument that the ERN/Ne is error-specific (Falkenstein, 2004a).

### **Reinforcement-Learning Hypothesis**

Holroyd and Coles (2002) argue that the ERN/Ne is produced during a reinforcement learning process. According to this theory, behaviour is monitored by an „adaptive critic’ located in the basal ganglia that distinguishes between events that are either better or worse than expected and initiates correspondingly altered dopaminergic activity. They put forward two basic assumptions regarding the reinforcement learning theory of the ERN/Ne; firstly, that the ERN/Ne is generated in the anterior cingulate cortex (ACC), and secondly that the ERN/Ne is one of several high-order executive functions that include an error processing system.

Executive function includes a range of systems that control human behaviour such as planning, decision making, working memory and response monitoring. There is a wide range of evidence that executive function or control is located in frontal

areas of the brain (Baddeley, 2007; Stuss & Knight, 2002), more specifically the anterior cingulate cortex (Baird et al., 2006; Botvinick, 2007; Krain et al., 2006); Osaka, Komori, Morishita, & Osaka, 2007), and the basal ganglia (Aron et al., 2003; Beste, Dziobek, Hielscher, Willemsen, & Falkenstein, 2009). Holroyd and Coles (2002) argue that response monitoring, the evaluation of action and intention, is likely to be related to an error-processing system linked to the production of the ERN/Ne component.

A wide range of evidence supports the view that the ERN/Ne may originate in the ACC (Holroyd & Coles, 2002). Animal studies have indicated altered ACC activity in the presence of negative feedback (Gemba, Sasaki, & Brooks, 1986) and Ito, Stuphorn, Brown, and Schall (2003) found error-sensitive cells in the ACC of macaque monkeys when errors were made during a saccade countermanding task. The role of the ACC in error processing is further supported by evidence from human neuroimaging studies that indicate increased ACC activity associated with erroneous responses compared to correct responses in choice reaction-time tasks (Lütcke & Frahm, 2007; Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004). Electrophysiological evidence, gathered from early investigations through to the present day, further supports the role of the ACC in error-processing. Researchers using dipole source localisation techniques have found data solutions that project to the ACC (Dehaene, Posner, & Tucker, 1994; Falkenstein et al., 1991) and the ERN/Ne is consistently found to have a fronto-central distribution again suggesting the ACC is a generator of this activity (Holroyd, Nieuwenhuis, Mars, & Coles, 2004; Falkenstein, 2004a; Falkenstein et al., 2000; Hajcak et al., 2003).

The mesencephalic dopamine system plays a crucial role in Holroyd and Coles' (2002) reinforcement learning theory of the ERN/Ne. This has emerged from animal

learning studies that have shown altered dopaminergic activity associated with predicted rewards and punishments, that is, when ongoing events are evaluated as better than or worse than expected. Holroyd and Coles go on to argue that ACC activity, reflected in the ERN/Ne, is a result of dopamine changes that occur during a reinforcement learning process that, in turn, trains the ACC to enhance performance.

Initial support for the reinforcement learning hypothesis of ERN/Ne was derived from simulation and experimental studies focussing on negative feedback and a resultant negative component with a similar topography to the ERN/Ne. In addition, simulated flanker task data generally matched experimental data, identifying appropriate positive and negative values according to frequency of presentation of compatible and incompatible flanker trials (Holroyd & Coles, 2002). The reinforcement learning hypothesis, however, does not provide an explanation for ACC activity and corresponding negative components that occur on correct trials (Yeung et al., 2004).

### **Conflict Monitoring Hypothesis**

Evidence of ACC activity on correct trials as well as error trials, particularly when there is a conflict between possible responses, has led to explanations of the ERN/Ne in terms of monitoring for conflict between possible correct and incorrect responses. Experiments using versions of a flanker task (Eriksen & Eriksen, 1974), where participants must respond to a target stimulus surrounded by congruent or incongruent distracters (e.g., H H H H H or <<<<< - congruent conditions; H H S H H or <<><< - incongruent conditions), result in differing levels of conflict between possible correct and incorrect response options. In an fMRI study using an arrowhead flanker task, Botvinick, Nystrom, Fissell, Carter, and Cohen (1999) noted ACC activity was greater for incongruent trials where conflict is argued to be high

compared to congruent trials where conflict is said to be low. Findings such as these provided the basis for a conflict monitoring hypothesis of ACC function. Botvinick, Braver, Barch, Carter, and Cohen (2001) suggested that this theory might offer a fuller explanation of ERP data associated with response monitoring and in particular the ERN/Ne.

Yeung et al. (2004) contend that when errors occur conflict arises as a result of differences between an executed incorrect response and the realisation of the correct response during continuing stimulus evaluation, and this is revealed in a response-locked negativity. They argue that the ERN/Ne reflects the process of monitoring for conflict between possible responses, but not an error detection process per se. They further point out that, rather than the ERN/Ne reflecting the output process of error detection, it does in fact reflect a contribution to this process.

Using a connectionist model developed from evidence from flanker tasks to explain the dynamics of response selection, Yeung et al. (2004) examined a selection of ERN/Ne data. In their simulation studies they found that much evidence from past studies could be explained adequately by their model. Findings from past research that indicate a larger ERN/Ne following responses to congruent stimuli compared to incongruent stimuli were, at face value, inconsistent with Yeung et al.'s theory. That is, the conflict monitoring theory would suggest that the ERN/Ne would be higher in high conflict incongruent trials. However, following simulation trials and consistent with past research, Yeung et al. found that a larger negativity was also evident on congruent trials when conflict was calculated as a difference between correct and error trials in congruent and incongruent conditions. When simulation data were further analysed separately, in terms of correct and incorrect responses and congruent and incongruent conditions, a clearer explanation emerged. Correct response



comparisons that occur during stimulus evaluation result in higher post-error activation on congruent error trials compared to incongruent error trials, due to the unequivocal characteristics of the congruent stimuli and thus produce a larger ERN on congruent trials.

The conflict monitoring hypothesis of the ERN/Ne has been challenged by researchers who have found a clear separation between ERN/Ne amplitude and levels of conflict. Masaki et al. (2007) investigated levels of conflict by manipulating difficulty in terms of stimulus brightness discriminability in a Simon task. Conflict was measured according to electromyogram (EMG) activations and was found to be greater for the easy compared to the difficult tasks, yet ERN/Ne amplitude did not vary according to task difficulty. Burle, Roger, Allain, Vidal, and Hasbroucq (2008) also found evidence to challenge the conflict monitoring hypothesis of the ERN/Ne. Using EEG and EMG activity in both simulated and experimental studies, and measuring conflict in terms of temporal overlap between incorrect and correct response activation, they determined that ERN/Ne amplitude decreased as the degree of conflict increased. They argue that this evidence brings into question one of the underlying assumptions of the conflict monitoring hypothesis, namely that the ERN/Ne is the electrophysiological marker of conflict monitoring.

### **Correct-response Negativity (CRN)**

The correct-response negativity (CRN) is a negative going deflection similar to the ERN/Ne that occurs between 50 ms and 100 ms following a response. Although CRN amplitudes are generally reported as smaller than the ERN/Ne, it has a morphology and topography not unlike that of the ERN/Ne and its source is also thought to be in the ACC (Simons, 2010). Early ERN/Ne researchers found little evidence of a negative component on correct response trials (Falkenstein et al., 1991;

Falkenstein, Hohnsbein, & Hoormann, 1995; Gehring et al., 1993), however later research indicated that a negativity also occurred following correct response trials (Falkenstein et al., 2000; Ford, 1999; Vidal et al., 2000). While Holroyd and Coles' (2002) reinforcement learning hypothesis of the ERN/Ne does not specifically explain corresponding correct response-related activity, they do argue that an evaluative process between better or worse than expected outcomes may take place. This, coupled with the comparative explanations of the mismatch hypothesis (Falkenstein et al., 1990), suggests that the CRN plays an important role in the overall explanation of error-processing.

In an experiment investigating age effects on ERN/Ne, Falkenstein et al. (2000) found that correct response trials completed during an Eriskson flanker task revealed a negative component at a similar latency to that of incorrect response trials, albeit with a smaller amplitude. When examining the psychophysiological markers of schizophrenia Ford (1999) found that, when completing a picture-word matching task, controls produced differentiated CRN and ERN/Ne amplitudes. In contrast patients with schizophrenia who responded correctly produced a CRN that was equal in amplitude to that of the ERN/Ne. Ford argued that this may suggest a failure to differentiate between response types amongst people with schizophrenia.

Vidal et al. (2000) investigated the ERN/Ne in terms of its specificity to error responses. They used surface Laplacians to determine topographical distributions of components from EEG data gathered while participants completed a simple choice reaction time task. They found that on both error and correct trials a negative going peak was evident at FCz and in view of this they contended that this component may not be representative of an error detection process but perhaps a response evaluation or comparison process. Vidal et al. go on to argue that if the generator of the

ERN/Ne is determined to be the ACC, which has been implicated in the control of autonomic responses related to affective behaviour, then it is not unreasonable to put forward the idea that this activity may represent some type of emotional processing of responses. Explanations of the CRN in terms of response monitoring or evaluation are also argued by Suchan et al. (2007). Data from two experiments using a continuous performance task revealed a clear fronto-central negativity occurring within a 0 to 100 ms post response time window irrespective of accuracy or trial type. This evidence, while challenging the idea that the ERN/Ne is specific to errors, suggests that the post-response components, both ERN/Ne and CRN, are part of a generic response evaluation process.

Coles et al. (2001) provide explanations of the negative components that occur on correct trials in terms of stimulus-related artefact or error-processing that takes place on these trials. They argue that error processing may occur on correct trials when participants are fatigued or when stimuli are difficult to distinguish. They also provide evidence from simulations of responses in data from a stimulus only presentation condition which indicated late stimulus-related negative deflections occurred at latencies corresponding to early response components. Coles et al. argue that such artefacts are probable in conditions where reaction times are likely to be short. Vidal, Burle, Bonnet, Grapperon, and Hasbroucq (2003) specifically investigated the possibility of overlapping stimulus-related and response-related potentials. Using data acquired from a Go/Nogo task, Vidal et al. compared stimulus-locked and EMG-locked averages. They found evidence of distinct stimulus related and response-related components in correct responses. It was argued that the latency of stimulus locked negativities occurred too early to impact response-related

components, thus indicating that the negativity seen on correct trials did not occur as a result of artefact contamination.

Falkenstein et al. (2000), considering data gathered from an Eriksen flanker task, drew on their mismatch hypothesis to explain the CRN. They suggested that early negative deflections on correct trials may reflect the representation of an error response even though a correct response was given. Falkenstein et al. (2000) go on to propose that this negativity might reflect a comparison process with the ERN/Ne a marker of a specific error response attenuating the activity. Scheffers and Coles (2000) noted a negative deflection on correct trials that displayed similar latency but smaller amplitude to the ERN/Ne during the completion of a letter version flanker task. They argued that this, and corresponding amplitude differences in ERN/Ne amplitude, may be a reflection of uncertainty in the overall response monitoring process. This was further confirmed by Pailing and Segalowitz (2004b) who conducted a series of studies designed to manipulate the level of discriminability of stimuli. They found that ERN/Ne and CRN amplitudes were more similar in the presence of uncertainty, suggesting support for an error detection hypothesis of early response-related negativities.

Evidence of the existence of the CRN has brought into question original reinforcement learning theories of the ERN/Ne and indicates that early response-related negativities are not specific to errors (Pietshmann, Simon, Endrass, & Kathmann, 2008; Simons, 2010). A growing body of evidence suggests that the CRN can be explained in terms of an error detection process and that both ERN/Ne and CRN amplitudes may index the level of certainty of responses (Pailing & Segalowitz, 2004b).

### **Error Positivity (Pe)**

Error positivity (Pe) has been noted as both a slow going positive wave and a positive peak that follows the ERN/Ne and has been reported to be maximal at the midline within a variety of time windows ranging from 150 ms to 750 ms post response. Reporting of the sagittal orientation of this component has ranged from Cz to Pz and points in between (Overbeek et al., 2005). A number of researchers investigating response monitoring have identified two positive components following erroneous responses: a peak approximately within a 0 – 250 ms post response time-window and a slow wave within a 250 to 750 ms post response time-window (Ruchow et al., 2005; Ullsperger & Szymanowski, 2004). Arbel and Donchin (2009) investigated the component structure of this ERP using spatio-temporal principal components analysis (PCA) and found two clear sub-components: one with a fronto-central orientation and the other with a centro-parietal orientation.

While the Pe has not been investigated to the same extent as the ERN/Ne, it is generally accepted that these components characterise independent elements associated with the processing of error responses (Falkenstein, 2004a; Nieuwenhuis et al., 2001; Overbeek et al., 2005). A number of hypotheses have been put forward to explain the functional significance of the Pe; however most of these explanations have focused on the early positivity. Explanations of this component include: recognition of conscious errors, alteration of response strategies following errors, and the processing associated with the motivational or emotional importance of an error. Some early investigations of the Pe found that this component demonstrated a similar morphology and topography to stimulus-evoked P300s and thus its explanation followed that of a P3 component.

### **Conscious error recognition**

Initial explanations of the early Pe in terms of response awareness put forward by Falkenstein et al. (2000) were not strong. While specifically investigating age effects on error-related ERP components they found that the Pe, measured within a 200 to 500 ms post response time window, was not necessarily evident in all subjects following an incorrect response. Falkenstein et al. (2000) argued that it was improbable that participants were unaware of their responses because this finding was coupled with significant post-error slowing in older subjects. Slower responses to stimuli immediately following an error were taken to indicate conscious error recognition. Further investigations began to gather evidence that strengthened the error awareness hypothesis of Pe. Nieuwenhuis et al. (2001) investigated error awareness in an antisaccade task in which errors were characterised by eye movements toward a cue when instructed to generate a saccade in the opposite direction. Participants were asked to indicate their awareness of incorrect movement with a button press and Pe was measured as the mean amplitude in a 200 ms time window beginning 200 ms following erroneous saccade-onset and quantified within difference waveforms (error minus correct). Nieuwenhuis et al. found that the Pe amplitude was larger for perceived errors compared to unperceived errors and interpreted this as a process of conscious error recognition. Additionally, Falkenstein (2004a) reported a reduced Pe, within a 200 to 500 ms post response time window, associated with errors in high difficulty tasks, where it may be more challenging to detect errors, compared to low difficulty tasks. This further supports the idea that the Pe reflects an awareness of errors.

In an investigation of the impact of negative response feedback on error-related components, Ehlis, Herrmann, Bernhard, and Fallgatter (2005) found clear ERN/Ne

and early Pe peaks to be evident following conventional errors but not following negative feedback to correct responses. They did however note a late positive deflection (500 to 800 ms post-response) in the feedback condition only. It is suggested that this late activity may reflect the conscious processing of the unexpected event and that overall the activity is a manifestation of an event-detection system that controls the processing of events that differ from what is expected (Ehlis et al., 2005)

More recently, Shalgi et al. (2009) investigated Pe and conscious error processing in an auditory Go/Nogo task. Following the presentation of each trial participants were given the opportunity to „fix’ erroneous responses by button press after consideration of their responses. This provided a measure of awareness of errors. Pe mean amplitude, measured in a time window 300 to 500 ms post-response was found to be significantly larger for aware („fixed’) errors compared to unaware („unfixed’) errors.

### **Response strategy updating**

The Pe has alternatively been explained as reflecting an adaptation of behaviour following an error. The majority of supportive evidence for this account stems from evidence of post-error slowing. Hajcak et al. (2003) conducted a study investigating the relationship between electrophysiological markers of error responses and autonomic measures including skin conductance and heart rate. Data from a modified Stroop task revealed a Pe peak that was defined as the most positive point within the 0 to 525 ms time-window following response onset. Among other findings, Hajcak et al. noted a positive relationship between the amplitude of the Pe and post-error slowing. Nieuwenhuis et al. (2001) used an antisaccade task to specifically investigate response awareness. Analysis of error-related data revealed post-error

slowing evident in perceived errors, but not unperceived errors, and Pe amplitudes derived from difference waveforms (error minus correct) were also reduced for unperceived errors. Taken together this evidence suggests that the Pe may be related to adaptive behaviour strategies following perceived errors.

### **Emotional error processing**

The explanation of the Pe as an affective or emotion-related process associated with error responses has some support. This hypothesis was first put forward by Falkenstein et al. (2000). Using data gathered during visual and auditory Go/Nogo tasks they argued that lower Pe amplitudes in high error rate conditions compared to low error rate conditions may reflect participant's subjective processing of the event. That is, when errors occur often, the event is less salient or important than when errors rarely occur and this is reflected in corresponding amplitude changes of the peak Pe measured in a time window 200 to 500 ms post error response. Evidence from source localisation analysis of data also provides some support for the notion that the Pe is connected with emotional processing. Analysis of incorrect response-related data, gathered when participants completed a flanker task, found the Pe to be localised to the rostral area of the ACC, which has been linked to affective processing (Herrmann et al., 2004).

### **Pe as a P3-like component**

The idea that the Pe can be explained as a P3-like component was put forward by a number of researchers (e.g., Falkenstein et al., 1991; Leuthold & Sommer, 1999; Overbeek et al., 2005). They suggest that this error related component has a similar topography and morphology to both the P3a and the P3b. Although generally reported as occurring more posteriorly than the frontal P3a and more anterior than



the parietal P3b, the Pe, as with the P3 components, is usually noted as displaying largest amplitudes at midline sites. Investigating error responses to visual and auditory tasks in focused and divided attention conditions, Falkenstein et al. (1991) found evidence of a later slow going positivity within a 500 to 700 ms post-stimulus time window. The researchers indicated that an explanation in terms of a delayed P300 was improbable since the overall delay would be approximately 150 ms for visual stimuli and 250 ms for auditory stimuli. Additionally, when amplitudes at Oz were considered in terms of stimulus-locked activity there was little difference between error and correct responses, whereas differences between response types were larger for response-locked activity. This indicated that the slow wave was specific to error trials and thus, Falkenstein et al. (1991) interpreted this activity as a second response-locked P300 that reflects processing of the erroneous response.

Leuthold and Sommer (1999) investigated error processing in visual and auditory stimulus-response compatibility tasks. Similar to Falkenstein et al. (1991), they found an early (approximately 400 ms post stimulus onset) and a late (approximately 600 ms post stimulus onset) positivity. The late positivity was found to be influenced by perceptual demands, that is, positive amplitudes were reduced in tasks with high difficulty compared to low difficulty in terms of discriminability. Leuthold and Sommer point out that this is similar to the effect of perceptual demands reported for P300 components. This, along with a centro-parietal scalp distribution, led Leuthold and Sommer to argue that the Pe may reflect similar processes. Thus, the early positivity is reflective of stimulus evaluation while the later positivity, error evaluation.

Ridderinkhof et al. (2009) also examined the similarities between P3 and Pe. They argued that if these components were functionally similar then the amplitude of

early Pe elicited during a Simon task would covary with target to target intervals in a visual oddball task. Their reasoning was based on the findings of Croft, Gonsalves, Gabriel, and Barry (2003), who determined that P3 amplitude was inversely related to the target to target interval duration rather than the target probability in oddball tasks. Ridderinkhof et al. found that early Pe amplitude, measured within a 100 to 300 ms post response time window, for the Simon task covaried with P3 amplitude differences associated with target to target intervals in the visual oddball task. Based on these findings Ridderinkhof et al. argue that, much like the P3 is seen to reflect the motivational significance of a stimulus, the Pe too may be an indicator of the motivational significance of an error.

Overbeek et al. (2005) conducted a comprehensive review of research to determine the dissociability of the Pe and the ERN/Ne. While acknowledging that there was much evidence for the independence of these components and some support for the error recognition hypothesis of the Pe, they point out some inconsistencies across the literature. A number of researchers used mean amplitude to quantify the Pe which resulted in the reported topography of this component to extend along the midline, whereas peak detection methods produced a more centrally focussed Pe. Differing measurement windows have also produced differing outcomes. Additionally, they note that complexity of task seems to impact the topography of the Pe. Overbeek et al. point out that differing quantification methods and measurement windows for this component prohibit a systematic comparison of research results.

### **Pc (Correct-response Positivity)**

Correct response activity (Pc) that corresponds to the Pe has not been systematically investigated, indeed only a handful of papers report analysis of this

activity and there is little discussion in terms of its functional significance. Many researchers argue that the Pe is a P300-like response to errors (e.g., Arbel & Donchin, 2009; Falkenstein et al., 1991; Leuthold & Sommer, 1999; Overbeek et al., 2005) that might be explained in terms of an oddball paradigm. More specifically, the Pe may reflect the infrequent or rare event that is the production of an error. If this is the case, then the Pc may be elicited by common correct responses and in fact represent the absence of the Pe. However, it should be noted that the explanation of the Pc as the absence of the Pe is not consistent with Falkenstein et al.'s (1990) mismatch hypothesis. These researchers put forward an explanation of error-monitoring as a relative, not absolute, process that is comparative in nature. If this is the case, then the Pe and Pc may indeed be components that represent the monitoring and evaluative process that occurs in terms of all responses.

Mathalon et al. (2002) investigated response monitoring irregularities in patients with schizophrenia. Data from a picture-word verification task indicated that while the control and schizophrenia groups both showed a clear Pe of similar amplitudes following errors, this positivity was not evident following correct responses within a 200 to 500 ms post response time window. Whereas the undifferentiated Pe was explained in terms task-specificity, the lack of Pc was not explained.

Kim et al. (2006) report the outcomes of an investigation of the correlates of response-related ERP components in patients with schizophrenia. Data associated with error responses in a Stroop task revealed reduced Pc compared to Pe amplitudes measured within a 150 to 250 ms post response time window for both control and schizophrenia groups but the groups did not differ in terms of amplitudes of each component. Again an explanation of the Pc component is not offered.

Burgio-Murphy et al. (2007) investigated response-related activity in children with behaviour and learning disorders. Analysis of data gathered from a discrimination task demonstrated a Pe-like component (Pc) on correct trials that was smaller in amplitude than the Pe. Burgio-Murphy et al. draw on Falkenstein et al.'s (1990) explanation of the slow going positivity (Pe) as a reflection of error monitoring and suggest that this process may occur to some degree on correct trials.

The absence of explanations of the Pc evident in the literature, is perhaps reflective an area of research that is in its infancy. As such it is essential to continue investigations in order to determine the functional significance of this activity. As Fabiani, Gratton, Karis, and Donchin (1987) pointed out in their early research on the P300 "...one does not proceed to develop a theoretical definition of a component before a wealth of observations suggest that there is indeed variance in the data that can be interpreted by assuming the existence of a component." (p. 4)

## **Summary**

Investigations of response monitoring, and in particular ERP components associated with both correct and error responses, have generated a great deal of research literature as well as a number of theories that attempt to explain early negative components occurring post response onset. The mismatch hypothesis explains this activity as a response identification process that reflects the detection of a mismatch between the actual error and the requisite correct response (Falkenstein et al., 1990). The conflict monitoring hypothesis put forward by Yeung et al. (2004) provides a somewhat similar explanation, however they suggest that the ERN/Ne is the manifestation of conflict between possible responses during continuous stimulus evaluation and not necessarily the detection or recognition of an error. Whereas these hypotheses include explanations involving a comparative aspect between correct and

error responses that are reflected in early response-related negative components, Holroyd and Coles' (2002) reinforcement-learning hypothesis does not allow for an explanation of negative components associated with correct responses. They instead suggest that the ERN/Ne reflects a reinforcement learning process that involves changed dopaminergic activity within the ACC that enables future enhanced performance. While neither the mismatch, conflict monitoring, nor reinforcement-learning hypothesis provides an unequivocal explanation for all research data, the evidenced response-locked negativities on both error and correct experimental trials suggests a generic evaluation process takes place following responses.

Positive-going ERP components, an early peak and a later slow going wave, have also been noted following responses and a number of explanations for this activity have been suggested. Whereas there is some empirical evidence to support the explanation of this component in terms of response awareness (Falkenstein, 2004a; Nieuwenhuis et al., 2001), it has also been linked to an affective or emotion-related process (Falkenstein et al., 2000; Hermann et al., 2004). Also, noted relationships with post-error slowing provide some substantiation of the explanation of the Pe in terms of behaviour adaption following errors (Hajcak et al., 2003; Nieuwenhuis et al., 2001). Since the Pe has been shown to have similar morphology and topography to the stimulus-evoked P3, explanations of this component have also been provided with reference to the motivational significance of the error (Falkenstein et al., 1991; Leuthold & Sommer, 1999; Ridderinkhof et al., 2009). Overbeek et al. (2005), however, point out that there are some inconsistencies in the literature. The use of differing quantification methods and differing measurement windows across a number of studies result in differing topographical distributions of activity and thus complicate the comparison process. Whereas the positive ERP

components associated with errors are beginning to be researched in more detail, corresponding correct response-related components have received little attention. A small number of researchers have reported these components, with fewer still offering explanations of this activity.

## Chapter 3

### **Factors Impacting Error and Correct Response-related ERP Components**

The investigation of the functional significance of various ERP components (ERN/Ne, CRN, Pe and Pc) associated with error and correct response processing has produced a number of theories which are not necessarily able to account for all data (Inzlicht & Bartholow, 2009). These components are all thought to be involved in executive processes that are argued to represent a monitoring and evaluative system (Falkenstein et al., 1991; Gehring et al., 1993). As such, much research has been directed toward developmental changes in executive processing that occur with age, and abnormalities or irregularities that may occur alongside psychopathology. A large body of research has provided evidence from animal, electrophysiological, and fMRI studies that areas in the frontal lobe, including the ACC, are involved at some level in the processing of responses (Dehaene et al., 1994; Falkenstein et al., 1991; Falkenstein, 2004b; Gemba et al., 1986; Holroyd & Coles, 2002; Ito et al., 2003; Lütcke & Frahm, 2007; Ridderinkhof et al., 2004). Since the ACC has been implicated in mood, emotion, and affective processing, so too have error components been explained in these terms (Gehring et al., 1993; Hajcak et al., 2004; Luu, Collins, & Tucker, 2000). Inextricably inter-related with these factors are experimental task types, task difficulty and response certainty or awareness that, along with personality traits that impact motivation and task salience, interact and modulate the effects of these factors (e.g., Dikman & Allen, 2000; Larson, Good, & Fair, 2010; Pailing & Segalowitz, 2004a; Santesso, Segalowitz, & Schmidt, 2005).

## Task Difficulty

One of the most common and well-known tasks used in experiments investigating response, and particularly error monitoring is the Eriksen flanker task (Eriksen & Eriksen, 1974). This task involves the presentation of a letter string or arrowhead stimulus (generally five) with the centre letter or arrowhead the target. It can be presented in either of two conditions – congruent (e.g., H H H H H or S S S S S/ <<<<< or >>>>>) or incongruent (e.g., H H S H H or S S H S S/ <<><< or >><>>). Although this task was originally created to examine the effects of distracting noise and response inhibition, it and its variations serve as a useful tool when investigating errors since with the increase in difficulty in the incongruent condition, participants are more likely to respond erroneously. Indeed, behavioural results support this with a lower error rate evident in congruent conditions compared to incongruent conditions (Eriksen & Eriksen). However, this task does not necessarily facilitate the investigation of the impact of task difficulty on error processing since very few errors are made in congruent conditions, often too few to create workable averages for ERP analysis.

The investigation of the influence of task difficulty on response-related ERP components has generated conflicting findings and in some cases it is not clear whether outcomes are necessarily due to the complexity of the task or may in fact be due to other task-specific factors. Falkenstein (2004a) reports the outcome of the comparison of ERN/Ne amplitudes between a flanker task, considered easy, and a Stroop task, considered difficult. While it is noted that the analysis of ERN/Ne and CRN amplitude, quantified within difference waves (error minus correct), showed the ERN/Ne peak amplitude to be “reduced and delayed for the more difficult tasks” (p. 7), care should be exercised in the interpretation of these findings since the tasks



are also fundamentally different and the resultant differences found in the ERN/Ne amplitude may also be attributable to task-specific factors and not difficulty alone.

Pailing and Segalowitz (2004b) investigated the effects of task difficulty by comparing responses to a standard letter version flanker task with two target letter choices to that of a modified letter version flanker task with three target letter choices. Peak analysis revealed ERN/Ne to be significantly larger than CRN. Whereas participants made significantly more errors and responded slower to the modified, more difficult, flanker task compared to the standard flanker, no significant amplitude differences were evident according to difficulty for either error or correct responses. Participants also reported no difference in subjective certainty of correctness of responses as measured by self-report post-test questionnaires. In light of this, Pailing and Segalowitz (2004b) go on to argue that in addition to ERN/Ne and CRN amplitudes not being influenced by task difficulty, ability to monitor performance levels was also not impacted by task difficulty.

The conflict-monitoring hypothesis of the ERN/Ne provides an explanation of this error-monitoring component in terms of the degree of conflict between possible correct and incorrect responses (Yeung et al., 2004). Thus, it is argued that manipulation of task difficulty may provide an avenue to explore this hypothesis further (Masaki et al., 2007). Masaki et al. varied stimulus discriminability in a Simon task between an easy: black squares on a white background or white squares on a black background and a hard: dark and light grey squares on a grey background condition. Whereas measurement of EMG activation was found to be greater in the easy compared to the difficult task, indicating clear differences, ERN/Ne amplitude did not vary according to task difficulty.

Hogan et al. (2005) investigated the development of the action-monitoring system in a group of adolescents (mean age = 15 years) and adults (mean age = 20 years). Participants were required to complete two forced-choice reaction time tasks with differing levels of task difficulty, easy: 2 choice and difficult: 4 choice. The researchers found no age differences in ERN/Ne amplitude in the easy task but the difficult task resulted in adults displaying larger ERN/Ne amplitude compared to adolescents. Hogan et al. point out that error rates were comparable across age groups, thus precluding an explanation in terms of understanding of the task requirements. The lack of age differences in easy tasks does not fit with previous explanations of an undeveloped response monitoring system in adolescents; consequently Hogan et al. put forward an alternative account. They suggested that age differences in ERN/Ne amplitude, evidenced as a function of task difficulty, may reflect maturational changes that shape the way in which other regions of the brain are engaged according to task demands. Hogan et al. also suggested that ERN/Ne generators may differ according to task difficulty.

Chang, Davies, and Gavin (2009) considered error monitoring in adults with ADHD. Participants were asked to complete a letter version of the Eriksen flanker task and associated data revealed the ERN/Ne peak amplitude to be significantly smaller in the ADHD group compared to controls whereas Pe peak amplitude revealed no significant differences across groups. Chang et al. discuss the findings associated with ERN/Ne amplitude in terms of atypical error processing and note the inconsistencies when compared to past studies. They suggest that these might be associated with varying task difficulty across flanker and letter discrimination tasks used in previous studies (Albrecht et al., 2008; Burgio-Murphy et al., 2007).

Since the ERP components associated with error processing have been argued to be a result of altered ACC and dopaminergic activity (Holroyd & Coles, 2002), a number of researchers have investigated these processes in patients with Parkinson's disease, a disorder known to involve dysfunction of the mesencephalic dopaminergic system (Falkenstein, Willemsen, Hohnsbein, & Hielscher, 2005). However, evidence from a number of these studies suggests that task difficulty or task specific factors play a role in response processing. Falkenstein et al. (2001) investigated error-monitoring in patients with Parkinson's disease where patients and controls were required to complete three tasks, including a modified Eriksen flanker task, a modified Simon task, and a complex Go/Nogo task. They found that ERN/Ne amplitude was significantly smaller in patients with Parkinson's disease compared to controls across all three tasks and concluded that this demonstrated impairment in error processing in patients with Parkinson's disease. In a follow up study, Falkenstein et al. (2005) investigated Pe in patients with Parkinson's and controls using the same three tasks. They found no significant differences in Pe amplitude between experimental and control participants, however grand means indicated distinctly different patterns of activity across flanker, Simon and Go/Nogo tasks that could be attributable to either task difficulty or other task-specific factors. Holroyd, Praamstra, Plat, and Coles (2002) found no significant differences in ERN/Ne amplitude between patients with Parkinson's disease and controls while completing a standard arrowhead version of the Eriksen flanker task. While Holroyd, Praamstra et al. conclude that this outcome demonstrates that the error-processing system may not be damaged in Parkinson's disease patients, or a slow progression of the disease in the sample used, the results might also be attributed to differences in task complexity across the experiments.

## **Conscientiousness**

Personality, at its broadest level, can be described as a set of characteristics that may influence motivation, thought and behaviours in various situations. Thus it is argued that response patterns may be reflective of these individual differences (McCrae & Löckenhoff, 2010). A number of ERP studies (e.g., Dikman & Allen, 2000; Pailing & Segalowitz, 2004a; Santesso et al., 2005) have been completed that indicate that personality characteristics or aspects of personality may play a role in the response monitoring processes, and in particular influence ERP components associated with this process. While the investigation of all personality characteristics and their influence on information processing may provide evidence in terms of evaluation of responses and subsequent influences on adaptive behaviour, this is beyond the scope of this thesis and as such the focus will remain on conscientiousness.

Conscientiousness is said to play a particular role in the control of goal-directed behaviour (McCrae & Sutin, 2007) and examination of this factor within the confines of response monitoring processes provides an opportunity to consider more specifically the importance or relevance of responses from an individual differences perspective. To date only one study is reported in the ERP literature where conscientiousness was specifically considered, however this occurred within an experimental paradigm that also included incentive manipulations according to response types (Pailing & Segalowitz, 2004a). Conscientiousness as a discrete factor in response monitoring is yet to be investigated. Pailing and Segalowitz (2004a), arguing that the salience of errors would be influenced by individual differences, investigated ERN/Ne, personality types, and levels of incentives for accuracy. Using a four-choice letter task and varying monetary incentives according to correct response types, they found no overall difference in the ERN/Ne between errors

according to incentive levels. While this outcome could be explained in terms of participant understanding of incentive manipulations and length of task (2080 trials), when personality type was included in the analysis it was found to be a moderating factor on ERN/Ne amplitude. That is, participants scoring high on conscientiousness scales showed lower incentive-related changes in the ERN/Ne and participants scoring low on Neuroticism were more likely to demonstrate ERN/Ne amplitude changes according to levels of incentive. Pailing and Segalowitz (2004a) point out that the negative relationship between Conscientiousness and Neuroticism evidenced in their study has an explanation based on the findings of cross-correlational studies of personality inventories. The connection appears to be locus of control, with high conscientiousness associated with low external control beliefs and high neuroticism related to higher levels of external control beliefs. This evidence suggests that the processes involved in response-monitoring are more complex than first thought, and should not be considered without some consideration of measures of individual personality traits.

Since ERN/Ne and other response-related ERP components have been demonstrated to be influenced by external motivational factors, such as incentives and rewards to produce correct responses (e.g., Gehring, et al., 1993; Hajcak et al. 2005) it is important to consider other aspects of motivation in terms of response-monitoring. Pailing and Segalowitz (2004a) suggest that measures of conscientiousness may assess aspects of performance or response-monitoring such as discipline and achievement-striving behaviour which are in turn recognised as characteristics of internal motivation.

From this perspective, Pailing and Segalowitz (2004a) argue that highly conscientious individuals may be more highly engaged in tasks compared to less

conscientious individuals and this is reflected in the ERP components said to measure response-monitoring. Thus measures of conscientiousness were included in this series of studies in an effort to examine the impact of internal motivation on response-monitoring.

### **Task and Response Salience**

Task or response salience has been implicated as an influencing factor on ERP components associated with response monitoring in a large number of studies. The measurement of task and response salience has taken many forms including personality measures that are said to reflect individuals' engagement and motivation to complete tasks accurately, monetary incentives, and evaluation by third parties. Dikman and Allan (2000) considered error-related activity in terms of low and high socialisation as measured by Gough's socialisation sub-scale (SO) (1994) of the California Psychological Inventory (CPI) (Gough, 1957). Participants scoring very high and very low on the SO completed a letter version of the Eriksen flanker task under conditions of reward and avoidance learning. In the reward condition, participants were instructed that they could earn money for correct responses and they received feedback only following incorrect trials indicating no monetary reward was gained. In the avoidance learning condition, participants received a loud tone following an incorrect trial or trials where no response was made. Again, no feedback was given following correct trials. Mean ERN/Ne amplitude was quantified within difference waves (error minus correct). Those participants who scored high on the SO showed no difference in mean ERN/Ne amplitude across reward and avoidance learning conditions whereas low socialisation participants showed larger mean ERN/Ne amplitude in the reward condition compared to the avoidance learning condition. Dikman and Allen offer three possible explanations for these outcomes.

Low socialisation participants may see errors as less important, monitor responses less intently, or believe the consequences of erroneous responses to be less in avoidance learning conditions compared to reward conditions. Dikman and Allen point out that the results of their research suggest that the ERN/Ne may be modulated by a range of individual differences that provide contextual information within which people evaluate their responses.

Santesso et al. (2005) examined personality factors and their association with ERN/Ne amplitudes in children. Participants were asked to complete a letter version of the Eriksen flanker task and analysis of this data revealed that children who scored high on the Psychoticism and low on the Lie scales of the Junior Eysenck Personality Questionnaire - Revised (Corulla, 1990) also displayed reduced ERN/Ne peak amplitudes. Other personality measures were found to be unrelated to ERN/Ne and Pe peak amplitudes. Regression analysis showed that a model including Psychoticism and Lie scale scores accounted for 20% of the variance in ERN/Ne peak amplitude. Further analysis revealed that only measures indicating social behaviours on the Psychoticism scale were related to the ERN/Ne. Santesso et al. (2005) argue that these personality measures reflect low socialisation in children, and suggest that the modulated ERN/Ne may be a measure of the inability to understand the impact of poor task performance and, since the ACC has been implicated in theories of ERN/Ne, a measure of ACC hypoactivity.

Larson et al. (2010) investigated positive personality traits and their relationship with ERN/Ne. Participants completed three self-report scales; Satisfaction with Life Scale (Diener, Emmons, Larsen, & Griffin, 1985); Life Orientation Test-Revised (Scheier, Carver, & Bridges, 1994); Positive and Negative Affect Schedule (Watson, Clark, & Tellegen, 1988) before also completing an

arrowhead version of the Eriksen flanker task (Eriksen & Eriksen, 1974) presented on a computer monitor. ERN/Ne amplitude was significantly larger than corresponding negativity on correct trials (CRN) and was maximal at FCz. Likewise, mean Pe amplitude was significantly larger than similar activity on correct trials and this activity was maximal at Cz. While significant weak to moderate correlations were revealed between CRN amplitude and positive affect (-.30) and between ERN/Ne amplitude and satisfaction with life scores (.32), no other correlations between measures of positive and negative personality traits and ERP response monitoring component amplitudes reached significance. Using regression analysis Larson et al. found that satisfaction with life measures was the only significant predictor of ERN/Ne amplitude. However, their overall model was not significant, with only 13% of the variance in ERN/Ne amplitude accounted for by satisfaction with life scores. The researchers argue that these findings may be explained in terms of motivation and response salience, with errors being less important to those who are more satisfied with life.

Investigations of personality factors associated with ERN/Ne, CRN, and Pe have indicated that personality traits may be a moderating factor in the processes involved in response monitoring. While few studies directly report causal relationships between component amplitudes and differing personality traits, when personality traits are considered as moderators in the process of determining task importance or salience and levels of motivation to complete tasks accurately a different picture emerges.

The association between ERN/Ne, and error salience was made in an early study by Gehring et al. (1993). Participants were required to complete an Eriksen flanker task in which speed, accuracy, financial rewards and penalties were



alternately emphasised. ERN/Ne amplitude was found to be larger when participants were rewarded for accuracy rather than fast responses. The researchers interpreted this as the accuracy instructions influencing the salience of errors. Similar to this outcome, in a study investigating response-monitoring in patients with schizophrenia, Morris, Yee, and Nuechterlein (2006) found that, whereas overall patients with schizophrenia displayed reduced ERN/Ne amplitudes compared to healthy controls, the ERN/Ne amplitude for both groups was significantly larger when response speed was stressed and accuracy was not. Again, this suggests task instruction influenced task salience and in turn impacted ERN/Ne amplitude.

Using an arrowhead version of the Eriksen flanker task, Hajcak et al. (2005) manipulated the value of errors in terms of monetary gain for correct responses as well as introducing experimenter evaluation, where participants were informed that their performance would be evaluated and compared to that of others, as possible influences on the importance of errors across two experiments. Larger ERN/Ne amplitude was found in high value (motivation) and evaluation conditions compared to low, leading the researchers to conclude that the magnitude of the ERN/Ne reflects the subjective importance of errors. CRN amplitudes were not impacted by levels of monetary gain or evaluation suggesting a functional separation of the ERN/Ne and CRN.

Reward and punishment sensitivity and error processing were investigated using a letter version of the Eriksen flanker task (Boksem, Tops, Wester, Meijman, & Lorist, 2006). Participants completed the Behavioral Activation System/Behavioral Inhibition System (BIA/BAS) scales (Gray, 1987; 1989), the Five Factor Personality Inventory (FFPI) (Hendriks, Hofstee, & De Radd, 1999) and the Temperament and Character Inventory (TCI) (Cloninger, Pryzbeck, Svrakic, & Wetzel, 1994) in order

to establish levels of punishment and reward sensitivity. Boksem et al. found that those who scored high on the BIS scale displayed larger ERN/Ne amplitudes than those who had low BIS scores and those who scored high on the BAS scale displayed larger Pe amplitudes. The researchers point out that, notably, personality traits related to punishment sensitivity, including neuroticism ( $r = .54$ ) and harm avoidance ( $r = .57$ ), were positively correlated with BIS scores. Likewise, reward seeking personality traits such as extraversion ( $r = .42$ ) and novelty seeking ( $r = .61$ ) were positively correlated with BAS scores. Boksem et al. contend that these outcomes suggest that the ERN/Ne may be related to negative motivation (e.g., punishment avoidance) while the Pe may be related to positive motivation (e.g., reward). Boksem, Tops, Kostermans, and Cremer (2008) further evaluated the suggestion of a relationship between error-processing components and reward and punishment sensitivity. In their between groups design experiment, participants were required to complete a letter version of the Eriksen flanker task in either of two conditions: where they were informed that accurate responses would be rewarded financially, or where incorrect responses would be penalised financially. Feedback was presented following each trial. As predicted, the ERN/Ne amplitude was found to be larger in the punishment compared to the reward absent condition for those who scored high in punishment sensitivity and also the ERN/Ne amplitude was larger in the reward absent compared to the punishment condition for those who scored high in reward sensitivity. Boksem et al. (2008) frame their interpretation of these outcomes in terms of the impact of the subjective value of the response. For example, participants who score high in punishment sensitivity and negative affect experience errors as more aversive in punishment conditions compared to those who score low in punishment sensitivity and negative affect. Boksem et al. (2008) go on to point out

that this is played out in the level of engagement in tasks, related motivation to avoid errors or gain rewards, and ERN/Ne amplitudes.

Similar to Boksem et al., (2006), Amodio, Master, Yee, and Taylor (2007), investigating the ERP correlates of the behavioural inhibition and activation systems, found the ERN/Ne to be positively correlated with BIS scores (Gray, 1987; 1989). Considering amplitudes of error responses in a Go/No-Go task, Amodio et al. also found the dipole modelled source of the ERN peak to be in the dorsal ACC. They go on to explain this activity in terms of the conflict monitoring hypothesis of the ERN (Yeung et al., 2004). Amodio et al. point out that Gray's (1987) description of the behavioural inhibition system (BIS) which is said to be sensitive to conflicts between opposing responses and unanticipated stimuli is not unlike the proposed conflict-monitoring function of the ACC. Specifically the ACC is argued to monitor for conflict between an executed incorrect response and the realisation of the correct response during a continuing stimulus evaluation process (Yeung et al., 2004).

The outcomes of studies indicating larger ERN/Ne associated with participants who were affectively distressed, worried, or reported high negative affective experiences (Gehring, Himle, & Nisenson, 2000; Hajcak et al., 2004; Johannes et al., 2001) have provided a rationale for researchers to include this in their conceptualisation of ERN/Ne and they argue that this activity may reflect a negative affective response to errors (Luu, Collins, & Tucker, 2000; Luu, Flaisch, & Tucker, 2000; Luu, Tucker, Derryberry, Reed, & Poulsen, 2003).

The connection between the frontal lobe, the ACC and executive function and the role they play in self-regulation and self-monitoring of behaviour, particularly processes involved in monitoring for errors, has been widely investigated (e.g., Luu, Flaisch et al., 2000). Luu, Collins et al. (2000) investigated negative affect and

negative emotionality and their impact on error monitoring in a study where participants were asked to complete a letter version of the Eriksen flanker task. Feedback regarding response accuracy was given following each trial and a level of incentive was introduced with participants penalised points for incorrect or late responses. Those who scored high in negative affect and negative emotionality, as measured by the Positive and Negative Affect Schedule (PANAS: Watson et al., 1988) and MPQ (Tellegen & Waller, 1996), displayed significantly larger ERN/Ne amplitude than participants who had low scores on these measures. However, this pattern of activity changed as blocks of trials progressed, with those high in negative affect displaying decreasing ERN/Ne amplitude across time while those low in negative affect displayed an ERN/Ne that remained relatively stable. Luu, Collins, et al. (2000) suggest that this may indicate disengagement with the task for those individuals high in negative affect. This evidence also implies that motivation and emotion should be included in explanations of regulatory behaviour, such as response monitoring.

Noting that ACC activity has been associated with response monitoring and regulation of affective responses, Hajcak et al. (2004) investigated the ERP correlates of error processing in terms of negative and positive affect. Using the PANAS (Watson et al., 1988) to determine three affect levels (low negative affect: low-NA; high negative affect/low positive affect: High-NA/Low-PA; high negative affect/high positive affect: High-NA/High-PA), groups completed a modified Stroop task. Hajcak et al. (2004) found that ERN/Ne peak amplitude and CRN peak amplitude were significantly larger for those who reported high levels of negative affect compared to those who reported low levels, whereas post-error activity was diminished. These effects were not moderated by level of positive affect. The

researchers argue that, since ACC hyperactivity is associated with negative affect, these results may reflect a heightened engagement within the response monitoring system.

A growing body of research on response monitoring, and particularly the ERP components associated with this executive function (ERN/Ne, CRN, and Pe), has reported motivational and affective influences on levels of task salience and task engagement, as well as the personality factors that may interact to modulate amplitudes of the ERN/Ne. This evidence suggests that this negativity reflects more than simply the recognition of an event; rather it may be an index of the affective response to the event taking place (Hajcak et al., 2004). These explanations may be particularly meaningful in that they provide an opportunity to measure the salience of outcomes that are essential to goal-directed behaviour (Pailing & Segalowitz, 2004a).

### **Response Awareness**

The association between response awareness and ERN/Ne and Pe amplitudes has been specifically investigated through a number of studies. Early ERN/Ne investigators suggested that the ERN/Ne was related to perception of response accuracy (Scheffers & Coles, 2000), whereas later studies have focussed on conscious awareness in terms of error-responses only and have looked to the Pe as a marker for this process.

Scheffers and Coles (2000) examined perceived and unperceived response accuracy when participants completed a two choice letter version of the Erikson flanker task. All participants were trained, via tone presentations, to respond with an activation force of 25% of their maximum voluntary squeeze force. They were then required to maintain this level within an accuracy range of 75% to 85%. Following this, task difficulty for each participant was adjusted, via contrast settings on the

computer monitor on which the stimuli were presented. Following each response, participants were required to further respond on a five point rating scale in terms of their perceived accuracy. This offered options of 'sure correct', 'unsure correct', 'don't know', 'unsure incorrect', and 'sure incorrect'. Scheffers and Coles found that overall ERN/Ne amplitude was larger for incorrect compared to correct trials. The researchers then sorted trials in terms of perceived accuracy rating and found that as participants' certainty of inaccuracy increased so too did the amplitude of the ERN/Ne. That is, irrespective of actual response, ERN/Ne amplitude varied according to perceived awareness of response type. The evidence of the significant linear trend of increasing ERN/Ne amplitude with perceived inaccuracy led Scheffers and Coles to argue that the ERN/Ne may reflect an error detection process. Nieuwenhuis et al. (2001) point out participants' subjective accuracy ratings may well be linked to the amount of information available from the variously degraded stimuli that were presented. They suggest that this evidence indicates that the ERN/Ne may not be reflective of error responses if there is insufficient information to identify the response type. Thus this evidence may also lend itself to an explanation of varying ERN/Ne amplitudes in terms of levels of task difficulty.

Nieuwenhuis et al. (2001) investigated both ERN/Ne and Pe components as a function of awareness of response. They used an antisaccade task where participants were instructed to initiate an eye movement in the opposite direction of a target presented on a computer screen. Whereas Scheffers and Coles (2000) required participants to respond to perceived accuracy on a five point scale following each response, Nieuwenhuis et al. (2001) required only a single button press if participants considered that they had moved their eyes in the direction of the target stimulus instead of away from the target. Target stimuli, task instruction, and therefore task

difficulty remained constant. The researchers argued that if the ERN/Ne and Pe are related to response awareness then these components would be impacted by direction error trials that were not identified as such. Nieuwenhuis et al. (2001), using difference waves to quantify peak ERN/Ne and mean Pe amplitude, found that, unlike Scheffers and Coles, an ERN/Ne peak followed all incorrect responses with no significant amplitude differences according to whether errors were perceived or not. On the other hand, they found the Pe amplitude, quantified within difference waves and a 200 to 400 ms post-response time window, was significantly larger on perceived compared to unperceived error trials. This evidence provides support for the notion that there are in fact two dissociable error monitoring processes reflected in the ERN/Ne and Pe, with the latter likely to be associated with subjective awareness of responses.

Endrass et al. (2005) replicated the findings of Nieuwenhuis et al. (2001) using a stop-signal task where responses were also indicated by eye saccades and awareness of responses was indicated following each trial. Quantifying mean ERN/Ne and mean Pe in the 70 to 110 ms and 200 to 400 ms post response time windows respectively, they found that, similar to Nieuwenhuis et al. (2001), Pe amplitude was significantly larger for perceived errors compared to unperceived errors with no difference in ERN/Ne mean amplitude according to levels of error awareness. Again, these outcomes were discussed in terms of separate early and late processing stages. The early stage was proposed to be an automatic process reflecting the detection of the generation of incorrect motor responses and the later processing associated with conscious awareness of errors. Endrass et al. (2007) further examined the ERP components associated with error awareness, again using an antisaccade task and extending previous work by considering early and later sub-components of

Pe. They determined measures of mean ERN/Ne within a 60 to 100 ms post response time window and mean Pe amplitude within several 100 ms time windows, 200 to 300 ms, 300 to 400 ms, 400 to 500 ms, and 500 to 600 ms post response. Mean ERN/Ne amplitude did not differ significantly in terms of awareness of incorrect responses. Also, early mean Pe amplitude, measured in two time windows, 200 to 400 ms post response, did not show differential awareness effects. On the other hand, the late Pe measured between 400 to 600 ms post response was found to be significantly larger for aware compared to unaware trials. Endrass et al. (2007) suggest that the Pe may be associated with remedial action since they also found significant post-error slowing in correct trials following an error. Overall, they argue that this evidence further supports the disassociation of the ERN/Ne and Pe components in terms of their functionality and indeed a functional separation of the early and late sub-components of the Pe. Endrass et al. (2007) further suggest that since the early Pe shares a similar topography to that of the ERN/Ne these components may also reflect a common role within the response monitoring system. However, they propose that the late Pe, displayed as positive parietal deflection beginning approximately 400 ms post response, reflects the time-course of the effects of conscious error awareness.

In a study specifically considering the role of the ACC, ERN/Ne and Pe, and error awareness, O'Connell et al. (2007) asked participants to complete a Stroop version of a Go/Nogo task and indicate erroneous responses with a button press. They found no differential awareness effects in terms of ERN/Ne peak amplitude and early (140 to 240 ms) post-response mean Pe amplitude. Conversely, late (300 to 500ms post-response) mean Pe amplitude was found to be only present when participants consciously recognised they had made an error and was significantly



larger for aware compared to unaware and correct responses. O'Connell et al. provided further evidence of the functional separation of the ERN/Ne and Pe by submitting their data to source localisation analysis techniques. This analysis demonstrated that the ERN/Ne and the Pe were both generated by the ACC however the ERN/Ne was evident in the caudal region with Pe appearing to be more anterior within the ACC. O'Connell et al. also examined cortical arousal, as measured by the power spectrum of the EEG, and found that a low ratio of slow/fast EEG activity, that is increased cortical arousal, was significantly correlated with increased awareness and larger mean Pe amplitude. O'Connell et al. suggested that the Pe may reflect the facilitation of information processing similar to a stimulus-related P3 and the ACC may be involved in the preconscious and conscious processes associated with error detection.

Investigating error awareness in an auditory Go/Nogo task, Shalgi et al. (2009) required participants to respond with a button press to syllables spoken aloud (Go), and withhold a response on other target syllables (Nogo). Participants also had the opportunity to „fix’ an erroneous response (responding in the Nogo condition) by pressing an alternative „fix error’ button should they have made a mistake. A level of motivation was introduced by informing participants of a reward for good performance. Similar to evidence gathered in visual (O'Connell et al., 2007) and antisaccade (Endrass et al., 2005, Endrass et al., 2007; Nieuwenhuis et al., 2001) tasks, ERN/Ne amplitude showed no significant difference for aware compared to unaware errors. Also similar to past findings, Pe amplitude (averaged at Pz within a 300 to 500 ms post response time window) was augmented for aware errors only. Shalgi et al. suggest that such evidence shows a clear link between Pe amplitude and response awareness as well as indicating that this component is not task or modality

specific. Shalgi et al. explored the explanation of the Pe further in terms of its stimulus-related and response-related properties. Based on similar morphology, topography and responsiveness to experimental factors they have suggested that the Pe is a delayed stimulus-related P3b (Donchin & Coles, 1988) or second P3 component (Leuthold & Sommer, 1999; Ridderinkhof et al., 2009). Examination of stimulus-locked and single-trials revealed a Pe following an aware error that demonstrated similar topography and morphology to a P3b following a correct withholding of response in the Nogo condition. Shalgi et al. point out that the Pe had a long latency and peaked after the response and since the Pe was clearly linked to awareness of responses then this component may reflect completion of stimulus processing manifested in a delayed P3b.

Chang et al. (2009) investigated error-related processing in adults with ADHD. Data gathered from a letter-version flanker task revealed the ERN/Ne peak amplitude to be significantly smaller in the ADHD group compared to controls and a similarity in Pe amplitudes displayed by the ADHD and control groups. This was discussed in terms of differential capabilities across two elements associated with error processing. That is, if the Pe reflects error awareness, then the results of this study in terms of ERN/Ne and Pe amplitudes taken together might reflect altered early preconscious processing coupled with intact error recognition processing in people with ADHD. However, evidence from a correlational analysis of Pe amplitudes and scores on the Task Monitor subscale of the Behavior Rating Inventory of Executive Function (BRIEF-A) (Gioia, Isquith, Guy, & Kenworthy, 2000) seem to contradict this. Pe amplitude was found to significantly correlate with scores on the Task Monitor sub-scale for the control group only. Since the Task Monitor sub-scale is said to reflect the ability to recognise and rectify mistakes, and if, as Chang et al.

point out, the Pe is intact in ADHD participants then a relationship between Pe and Task Monitor sub-scale scores should also be evident in this group.

Kim et al. (2006) investigated error-monitoring in patients with schizophrenia and healthy controls using a standard Stroop task. Averaged response-locked EEG data were submitted to peak amplitude and latency analysis and, similar to previous studies, ERN/Ne amplitude was decreased and CRN amplitude was increased in patients with schizophrenia compared to controls. No difference was found in Pe peak amplitude and corresponding correct response-related late positivity (Pc) amplitude across both groups of participants. Similar to previous studies (e.g., Ford, 1999), the schizophrenia group showed no significant difference in ERN/Ne and CRN amplitudes. Kim et al. explain these findings as reflecting impaired response monitoring in patients with schizophrenia compared to controls, with the lack of difference in ERN/Ne and CRN amplitudes in patients with schizophrenia suggesting that these participants are unresponsive to errors. Kim et al. point out that if, as past researchers have indicated, Pe reflects error awareness then in this instance the similarities in Pe amplitudes across schizophrenia and control groups suggest both groups perceived errors in a comparable manner. The researchers further suggest that this may be the case due to the ease of the task; however this interpretation seems somewhat tenuous since perceived awareness was assumed and not directly measured. Kim et al. put forward an alternate explanation based on a lack of an evidenced relationship between Pe amplitude and executive function measures. They suggest that Pe may in fact be related to other cognitive functions but they neglect to clearly explicate what these functions might be.

When Mathalon et al. (2003) examined response-monitoring in patients with Alzheimer's disease using a picture naming task that involved naming a presented

picture one week from first viewing, they found that the ERN/Ne was reduced compared to controls. Whereas this has generally been attributed to ACC dysfunction, Mathalon et al. point out that Alzheimer's disease patients often display fibre disruption to the pre-frontal cortex and not the ACC. Additionally, a trend approaching significance was apparent for Pe amplitude to be reduced in patients with Alzheimer's disease compared to controls. Similar to findings obtained in studies of patients with schizophrenia, patients with Alzheimer's demonstrated no amplitude differences between ERN/Ne and CRN, however when CRN was analysed as a separate component Mathalon et al. found that patients with Alzheimer's displayed significantly smaller CRN amplitude compared to age-matched controls. The enhanced CRN compared to ERN/Ne amplitude was explained in terms of response certainty. Since patients with Alzheimer's who correctly responded to pictures that could not be named the preceding week, Mathalon et al. reasoned the larger CRN could be attributed to the uncertainty of responses.

One of the first investigations of response monitoring in the elderly was conducted by Band and Kok (2000). They required a group of younger (18-28 years) and older (60-76 years) participants to complete mental rotation tasks of varying difficulty where the letters G and R were presented either mirrored or normal, and rotated either 45° or 135°. ERN/Ne amplitude was found to be significantly smaller in elderly participants compared to young participants. Band and Kok also considered these findings in terms of error response corrections. They found that older participants corrected fewer errors than younger participants in the difficult task compared to the easier task, and they argued that this might reflect uncertainty of response requirements in the difficult rotation condition. The findings that ERN/Ne were reduced in older, compared to younger adults, were confirmed in a

study conducted by Nieuwenhuis et al. (2002). However, behavioural results from data gathered during the completion of a letter version of an Eriksen flanker task did not support the explanation of the difference in ERN/Ne amplitude between young and old participants in terms of impaired representation of required responses. In the incongruent flanker condition, where certainty could be compromised due to distracting incongruent flankers, older participants did not show a significant difference in reaction time or error rates compared to younger participants. Supporting this was evidence from the congruent flanker condition where similarly reduced ERN/Ne amplitude in older adults was noted. Nieuwenhuis et al. argued that it is unlikely that this would be due to ambiguity of response options since the target stimuli and flankers in this condition are the same.

### **Task-specific Factors**

In their review of 32 studies Overbeek et al. (2005) point out that inconsistencies in the literature on response-related processing may be attributable to differing ERP scoring methods. Such contradictions may also be a result of task-specific factors since researchers used a range of differing experimental tasks. Burgio-Murphy et al. (2007) investigated error-related responses in a letter discrimination task in groups of children diagnosed with behavioural and learning disorders. Unlike Albrecht et al. (2008), they found that ERN/Ne amplitude was larger for the ADHD group compared to controls. Given that behavioural data was comparable across these groups, Burgio-Murphy et al. describe the augmented ERN/Ne as reflecting an adaptive monitoring process that may be present in children with ADHD. That is, at a preconscious level, children with ADHD may be more aware of responses and as such be able to modify their behaviour to match levels achieved by children without ADHD. They also provide an alternative explanation of the heightened ERN/Ne in

children with ADHD. Drawing on evidence from studies investigating personality factors and their relationship with ERP components associated with response monitoring, Burgio-Murphy et al. suggest that children with ADHD may be more emotionally sensitive to errors. The researchers note, however, that their basic finding of larger ERN/Ne amplitude in children with ADHD compared to those without this diagnosis is at odds with other researchers' findings. Similar to Albrecht et al. (2008), Liotti et al. (2005) found ERN/Ne amplitude to be significantly reduced in children with ADHD using a Stop Signal task, whereas Wiersema, van der Meere, and Roeyers (2005) using a Go/Nogo task, found no significant differences between controls and an ADHD group. These findings, together with those of Burgio-Murphy et al., who used a letter discrimination task, suggest that findings in children with ADHD may be either task-specific or related in some way to the perceived task complexity.

Response-monitoring in patients with obsessive-compulsive disorder (OCD) has been variously investigated by a number of researchers. Hajcak and Simons (2005) measured EEG activity while participants completed a modified Stroop task. Participants with high obsessive compulsive characteristics showed augmented ERN/Ne and CRN amplitudes compared to those with low levels of obsessive compulsive characteristics although no performance differences were evident. Hajcak and Simons suggest that these results may reflect a hyper-functioning of the systems associated with action-monitoring. Nieuwenhuis, Neilen, Nisan, Hajcak, and Veltman (2005) also examined error-monitoring in patients with OCD. Data gathered from a probabilistic learning task revealed no significant differences in ERN/Ne amplitude between patients with OCD and controls. Nieuwenhuis et al. suggest that the divergent results in terms of error-monitoring and its association with OCD

across research studies may be attributable to differing experimental design, levels of medication or co-morbid disorders. Ruchow et al. (2005) examined the electrophysiological markers of OCD in controls and patients with OCD using a Go/Nogo task. Group differences were restricted to ERN/Ne amplitude and patients with OCD displayed enhanced negativity compared to controls. While Ruchow et al. indicate that the results may support the idea that augmented ERN/Ne in patients with OCD reflects hyper-functioning of error-monitoring systems and a clear dissociability between ERN/Ne and Pe, differences in outcomes across studies were also discussed in terms of their task-specific nature.

Gründler, Cavanagh, Figueroa, Frank, and Allen (2009), drawing on evidence from their study investigating ERN/Ne amplitudes associated with differing tasks in patients with OCD, suggest that task specific differences may be moderated by the level of OCD symptomatology. The researchers found ERN/Ne amplitudes to be enhanced in a flanker task for patients displaying high levels compared to those with low levels of OCD symptomatology. However, ERN/Ne amplitude elicited during a probabilistic learning task did not differ significantly as a function of OCD symptoms. Gründler et al. argue that this evidence suggests that there may be different neural mechanisms underlying the ERN/Ne in OCD patients: one reflecting the execution of an erroneous motor response and the other reflecting a less than optimal choice in a reinforcement learning task. While Olvet and Hajcak (2009) acknowledge that this may be the case, they also suggest that the absent or reduced ERN/Ne evidenced in a probabilistic learning task may in fact represent the effect of trial-to-trial feedback administered in the task. This argument is supported by evidence from their study which considered the relationship between anxiety, response feedback and ERN/Ne amplitudes. The finding that trial-to-trial feedback

moderated the relationship between ERN/Ne amplitudes and levels of anxiety was explained in terms of feedback reducing the burden of monitoring responses in more anxious individuals.

Mathewson et al. (2005) considered age effects using an Eriksen flanker task and a source memory task. They found that overall, older adults were not as accurate as younger adults and both ERN/Ne and Pe amplitudes were significantly lower for older compared to younger adults. Clear task differences were also found associated with Pe amplitudes, measured as the most positive peak in the 150 to 350 ms post response time window. Pe produced from a source memory task was diminished compared to that produced when participants completed a flanker task. Researchers using source localisation techniques found that the Pe associated with the source memory errors was located more posteriorly than that associated with flanker task errors. Mathewson et al. explain ERN/Ne differences with reference to the reinforcement learning hypothesis and decreasing dopaminergic activity in the aged. On the other hand, they suggest that the task related differences evidenced in Pe amplitudes may reflect the allocation of attention to an internal error signal and clearly indicate a functional separation of early negative and later positive response-related components.

Response monitoring has, for the most part, been investigated using non-linguistic tasks, for example, versions of the Eriksen flanker task, Go/Nogo task, Stroop Task or forced-choice reaction time tasks (Falkenstein et al., 2004a; Hajcak et al., 2005; Nieuwenhuis et al. 2002; Scheffers & Coles, 2000). However, more recently a number of researchers have begun to investigate response monitoring using differing language based tasks. In a study of Spanish-Catalan bilinguals, Sebastian-Gallés, Rodríguez-Fornells, Diego-Balaguer, and Díaz (2006) required



participants to complete lexical and phonological decision tasks derived from Catalan. Non-words were constructed by changing one vowel in an existing word. Whereas Catalan dominant bilinguals demonstrated amplitude differences between ERN/Ne associated with phonological decision task errors and correct responses to lexical decision tasks, Spanish dominant bilinguals showed no differences. In the absence of feedback concerning accuracy of responses, Sebastian-Gallés et al. explain these outcomes in terms of certainty of the correctness of responses, with Spanish dominant bilinguals unable to differentiate with certainty between Catalan words and nonwords in general, and amplitude differences reflecting greater certainty of responses in Catalan-dominant compared to Spanish dominant bilinguals.

Ganushchak and Schiller (2008) investigated errors in verbal self-monitoring and their impact on associated error response-related ERP components. Participants completed a Go/Nogo task that required them to internally name pictures as well as monitor for, and respond to, target phonemes within the names. Pictures were presented with or without auditory distractors that were either semantically related or unrelated to the target picture. ERN/Ne amplitude was found to be largest following errors when semantically related compared to semantically unrelated distractors were presented with targets. This pattern of activity was similar for the stimulus-related N450 amplitude. The semantic interference effect evidenced in ERN/Ne amplitudes is explained in terms of levels of response conflict associated with semantically related distractors. While this explanation fits within the conflict monitoring hypothesis (Yeung et al., 2004) of the ERN/Ne it also matches with Collins and Loftus' (1975) hypothesis of levels of conflict that occur within a spreading

activation theory of semantic processing and highlights a connection between explanations of stimulus-related and response-related components.

Horowitz-Kraus and Breznitz (2008) considered error processing in people with dyslexia and regular readers with real words and pseudowords presented individually in a computer-based lexical decision task. ERN/Ne peak amplitude, measured at Cz within a 30 to 100 ms post response time window, was found to be significantly larger for errors involving real words compared to pseudowords for regular readers. Horowitz-Kraus and Breznitz explain this in terms of the mismatch hypothesis of the ERN/Ne (Falkenstein et al., 1990), with this amplitude difference representing a greater mismatch between actual and required responses in each condition. They point out that the lower amplitudes to pseudowords may indicate the absence of the required response in the mental lexicon. It was argued that the significantly reduced ERN/Ne amplitude in people with dyslexia compared to controls in both conditions may represent inadequate knowledge of correct word patterns that may in turn have impacted the development of an error detection system associated with reading.

The investigation of error processing is beginning to be extended beyond that of simple reaction time tasks into the linguistic field. While a limited number of studies have been conducted in this area, explanations of response-related data have not been restricted to specific response-related theories. Researchers such as Ganushchak and Schiller (2008) have offered credible explanations of task-specific outcomes that combine theories of both stimulus and response-related ERP components.

### **Functional Separation of Response-related Components**

The dissociability of response-related components has been the focus of much research, particularly the functional separation of ERN/Ne and Pe (Overbeek et al., 2005). However not all researchers report or indeed investigate all components and as such the associations between early and late response-related components are not always clear. Whereas distinct explanations of these components have emerged, and are supported by differential time courses and scalp distributions, some researchers report that ERN/Ne and Pe are similarly impacted by experimental conditions.

Hajcak et al. (2005) investigated the motivational significance of errors across two experiments involving differing types of incentives to be correct: monetary gain and comparison to others' performance. They reported larger ERN/Ne amplitude in high value (motivation) and evaluation conditions compared to low. Hajcak et al. (2005) also noted that activity following the ERN/Ne differed for each experiment, with larger positive activity associated with the evaluation condition and sustained negative activity associated with the motivationally salient (high value) condition. Although this difference was not specifically analysed the researchers suggest that later response-related components may also be influenced by the motivational significance of tasks (Hajcak et al., 2005).

Arbel and Donchin (2009) investigated the component structure of post-error ERPs using data gathered from two experiments where participants completed variations of flanker tasks (Eriksen & Eriksen, 1974). Researchers varied the instruction for completion of the task across two conditions in Experiment 2: one condition emphasised speed, the other emphasised accuracy, of response. In Experiment 1, speed and accuracy instructions were not given. Principal Components Analysis (PCA) of data from both experiments revealed two topographically

separate, positive components: one with a fronto-central distribution and one with a centro-parietal distribution. Further analysis showed ERN/Ne amplitude to be greater in the accuracy condition compared to the speed condition, but no such difference was evident in the fronto-central positivity. Interestingly, the centro-parietal positive component was similarly sensitive to accuracy instructions as was the ERN/Ne. Thus, Arbel and Donchin (2009) argue for the dissociability of the fronto-central Pe and the ERN/Ne, but not the centro-parietal Pe. They also raise the interesting point that the Pe may in fact be a series of distinct components, which previously may not have been considered.

Investigations of developmental differences in response-related processes provide some evidence that early negative and early positive components are functionally different; however these findings are not always consistent. As such explanations in terms of maturational changes may be problematic and thus highlight the need to systematically investigate the functional separation of response-related components. Davies, Segalowitz, and Gavin (2004) investigated response-related data gathered during the completion of a letter version of an Eriksen flanker task. Participants were grouped according to age (ranging from seven to 25 years). The investigators noted that ERN/Ne amplitude increased according to age, whereas Pe amplitude did not change. CRN amplitude followed a very different pattern, with increases evident across younger age groups followed by a decrease in amplitude apparent in age groups ranging from ten years to mid teens and thereafter very little change occurring in age groups up to age 25 years. Davies et al. draw on Holroyd and Coles' (2002) reinforcement learning hypothesis of the ERN/Ne to interpret these outcomes in terms of the development and continuing process of maturation of the ACC and the mesencephalic dopamine system in children.

Ladouceur, Dahl, and Carter (2007) considered developmental changes in ERP components associated with response monitoring and corresponding neural generators in early adolescents, late adolescents, and adults. Participants were required to complete an arrowhead version of the Erikson flanker task and analysis of response-related data revealed similar findings to those of Davies et al. (2004). Ladouceur et al. found that ERN/Ne amplitude increased with age and source localisation techniques determined a source within the ACC. However, while Pe was evident for each age group and was also localised to the ACC, its amplitude differed with age: the late adolescent group displayed larger Pe amplitude than the adult group. Similar to previous researchers, Ladouceur et al. explained the ERN/Ne amplitude changes in terms of the maturation of the ACC, although this did not provide a clear account of the changes in Pe amplitude across age groups. On examination of post-experiment questionnaire data, they point out that the late adolescent group scored high on negative feelings associated with making errors and high on error response certainty. From this they suggest that the Pe may be related to emotional processing associated with erroneous responses or error awareness. However, this interpretation should be approached cautiously as it is based on data gathered from a small sample ( $n = 5$ ).

Santesso, Segalowitz, and Schmidt (2006), seeking to address the problem of small sample sizes noted in previous research and considering specific age related changes in the CRN as a reflection of error detection and certainty of response, recruited 39 children (mean age = 10.2 years) and 28 adults (mean age = 22.7 years). Analysis of data gathered from a letter version of the Eriksen flanker task showed that the ERN/Ne amplitude was larger for adults compared to children, lending support to the idea that the ACC matures later in terms of response monitoring. No

difference in Pe amplitudes, measured in a 200 to 500 ms post response time window, according to age were found parietally, however this was not the case frontally or fronto-centrally with adults displaying significantly larger Pe amplitudes than children. Santesso et al. (2006) suggest that this might be explained in terms of post-error processing differing for children. Evidence from analysis of the CRN was less definitive. The researchers undertook analysis of this component using three methods of quantification; CRN peak deviation from baseline, stimulus P3 peak to CRN peak, and CRN peak to following positive peak. In each case, analysis revealed different outcomes. CRN amplitude measured as a deviation from baseline, while found to be significantly different across Fz, FCz, and Cz for children, revealed no significant age differences. The CRN quantified from preceding P3 to CRN peak was shown to be maximal at Cz with no significant age group differences. However, CRN scored as a difference from the subsequent positive peak was found to be significantly larger for children compared to adults. Following hierarchical regression analysis, Santesso et al. (2006) found this difference was due to a separate source of variance than that associated with the ERN/Ne and concluded that these processes were independent of each other. Perhaps this conclusion should be considered cautiously as the justification for the follow up analysis was that the ERN/Ne and CRN differed as a function of age on one measure when no significant difference was evident on two other measures.

Since the ERN/Ne, CRN, Pe and Pc are suggested to be associated with executive function and control this provides a rationale to investigate error processing and response monitoring across various groups diagnosed with behavioural disorders. Albrecht et al. (2008) investigated error processing in groups of boys with ADHD, their non-affected siblings and controls. Data gathered from a

flanker task revealed a linear pattern in terms of ERN/Ne amplitude with the ADHD group displaying the smallest amplitude, followed by non-affected siblings and the control group showing the highest amplitude, with only the ADHD group and control group difference reaching significance. These findings were explained in light of dopaminergic dysfunction. No difference was found in Pe amplitudes across the three groups, indicating a clear dissociation between the ERN/Ne and Pe and suggesting that the Pe is independent of the dopamine system.

In 2005, Falkenstein et al. replicated the findings of the 2001 experiment investigating error-monitoring in patients with Parkinson's disease where patients and controls were required to complete three tasks, including a modified Eriksen flanker task, a modified Simon task, and a complex Go/Nogo task. They found that ERN/Ne amplitude was significantly smaller in patients with Parkinson's disease compared to controls across all three tasks and concluded that this demonstrated impairment in error processing in patients with Parkinson's disease. Falkenstein et al. further extended the analysis to included Pe, measured at Pz within the 250 to 550 ms post response time window. Whereas all tasks revealed a diminished ERN/Ne in patients with Parkinson's disease compared to healthy controls, Pe amplitude did not differ across groups. This demonstrates the dissociability of the ERN/Ne and Pe and suggests that the Pe is not linked to the dopaminergic system (Falkenstein et al., 2005).

## **Summary**

The investigation of response-related-processes and associated ERP components has revealed inconsistent findings in terms of the influence of task difficulty (e.g., Falkenstein 2004a; Hogan et al., 2005; Masaki et al., 2007; Pailing & Segalowitz, 2004b). However, a number of researchers point out that these inconsistencies may

be attributable to other task-specific factors, and consequently a challenge remains for researchers to disentangle the impact of these factors on response-related processes. Response awareness, as well as individual differences, have also been found to modulate response-related ERP components; however, again, inconsistent evidence complicates explanations of response monitoring (Falkenstein et al., 2004a; Ganushchak & Schiller, 2008; Masaki et al., 2007; Nieuwenhuis et al., 2001; Pailing & Segalowitz, 2004a). ERN/Ne, and to a certain degree CRN, have been investigated more fully than early and late Pe and corresponding correct response-related components (Pc). Moreover, researchers have not necessarily investigated or reported data relating to all response-related components in terms of experimental conditions. Considering these research outcomes it is difficult to establish a comprehensive explanation of the executive processes associated with response monitoring and questions as to the role of all response-related components remain to be answered.



## Chapter 4

### Rationale

The general aim of this series of three experiments was to systematically investigate response-related ERP components in terms of task salience, task difficulty, task specificity, response awareness, and conscientiousness. When considered as whole, investigations and subsequent explanations of ERN/Ne, CRN, early and late Pe, and corresponding early and late Pc provide a somewhat incomplete picture. As Inzlicht and Bartholow (2009) point out, since the first reports of the ERN/Ne in the early 1990s, this and associated ERP components “have become one of the most vigorously explored topics in psychophysiology” (p. S15). A number of theories have been suggested to explain both the ERN/Ne and Pe; however, to date none have been able to fully account for all research evidence (Inzlicht & Bartholow, 2009). The disparate and, at times, inconsistent findings across experimental paradigms and conditions provide an opportunity and need to investigate all response-related components in terms of the prevailing experimental conditions in an effort to clarify some of the processes involved in the generation of response-related ERP components.

An abundance of evidence is available within the current research literature focusing on the developmental and psychopathological factors that impact response-related components. Most researchers have explained early differences in terms of maturational changes or dysfunction within the ACC and related dopaminergic activity. However, a number of researchers have reported task-specific changes in one or more response-related components that are somewhat difficult to reconcile with overall explanations of this activity. On the one hand ERN/Ne has been found to

be modulated by age related differences while Pe was not (Davies et al., 2004; Mathalon et al., 2003); on the other ERN/Ne amplitude differences according to age were only evident in difficult compared to easy tasks (Hogan et al., 2005). CRN amplitudes have been evidenced to display age related differences (Davies et al., 2004), although other researchers reported that this change was dependent on the method of component quantification (Santesso et al., 2006). Pe has been reported to differ in amplitude according to task type (Mathewson et al., 2005); however since this component has been quantified within various time windows across a number of studies, systematic comparisons are not possible (Overbeek et al., 2005).

Similar discrepancies are evident when response-related ERP components are considered in terms of task or response importance and individual differences related to personality traits and motivation. Motivation, measured as a function of incentive or evaluation, has been found to modulate ERN/Ne amplitudes (Hajcak et al., 2005; Morris et al., 2006). Other researchers have found the subjective importance of responses to be reflected in ERN/Ne amplitudes when individual personality differences were taken into account (Dikman & Allen, 2000; Pailing & Segalowitz, 2004a). Again, while Pe is investigated in some studies, diverse quantification methods and time-windows do not allow conclusions to be drawn regarding the influence of task or response salience on this component.

Pe has been variously researched in terms of a number of posited explanations for this component, with a considerable body of research evidence indicating that this component alone may be reflective of error recognition or awareness (Endrass et al., 2005; Nieuwenhuis et al., 2001). Furthermore, some researchers report the modulation of Pe amplitude according to response awareness or certainty at early and not late latencies (Endrass et al., 2005) and vice versa (Endrass et al., 2007). This is

also the case in terms of the topography, with differences reported at frontal areas (Hajcak et al., 2004; Mathalon et al., 2003) and conversely, at parietal areas (Falkenstein et al., 2005). ERN/Ne and CRN amplitude changes have also been linked to perceived response accuracy (Mathalon et al., 2003; Scheffers & Coles, 2000). Whereas ERN/Ne, CRN and Pe have been vigorously investigated, late correct response positivities (Pc) have been somewhat neglected, with only a small number of researchers including this component in reports of investigations (e.g., Burgio-Murphy et al., 2007; Kim et al., 2006). Few researchers have offered explanations of this activity, indeed some suggest that the Pc reflects the absence of a Pe rather than a component per se, while still others argue that this component is representative of comparative response monitoring process (Falkenstein et al., 1990).

Contradictory and inconsistent findings across a large body of research indicate a need for a systematic comparison of all response-related ERP components that are posited to represent a response-monitoring executive process. Since most theories of early negativities indicate, either directly or indirectly, a comparative process occurring between correct and error responses, and many instances are reported where experimental variables modulate both early negativities and later positivities differentially, investigation of the impact of antecedent conditions on all components is necessary.

In order to address these issues, three experiments were conducted to examine early and late, error and correct related components in terms of task difficulty, conscientiousness, task and response salience, and response awareness. Task difficulty and task specificity were investigated using an Eriksen (1974) flanker task and a phonological decision task. All tasks included a response awareness question designed to determine participant's certainty of response type (error, correct). The

inclusion of a conscientious variable (high, low) allowed examination of the impact of conscientiousness on response-related components.

## **Chapter 5**

### **Experiment 1:**

#### **Response-related Processes and the Influence of Conscientiousness, Task Difficulty and Response Awareness: Evidence from a Two-choice Flanker Task**

The discovery of an ERP component that reliably occurs following both error and correct responses has resulted in this activity being explained as a manifestation of general response-monitoring processes (Falkenstein et al., 1991). Whereas a number of theories focus on information processing (Holroyd & Coles, 2002; Yeung et al., 2004), a further body of research has demonstrated that motivational and personality factors may modulate early response-related components, indicating that response-monitoring processes are more complex than originally thought and that this evaluative function may be driven by underlying individual differences. However, it is not clear whether the impact of these factors is confined to early negative or extends to later positive response-related components (Hajcak et al., 2005; Pailing & Segalowitz, 2004a). The interplay between task difficulty and task-specific factors and their influence on response-related components is also yet to be clarified (e.g., Falkenstein, 2004a; Hogan et al., 2005; Masaki et al., 2007; Pailing & Segalowitz, 2004b). Response-related components have also been reported to reflect a subjective awareness of errors, however, conflicting evidence has been noted throughout the literature in this area (Endrass et al., 2005, Endrass et al., 2007; Nieuwenhuis et al., 2002; O'Connell et al., 2007; Pailing & Segalowitz, 2004a; Scheffers & Coles, 2000; Shalgi et al., 2009). These differences may be attributable to differing component

quantification methods, differing measurement windows (Overbeek et al., 2005) or differing manners in which awareness of responses are indicated by participants.

Considering these findings, Experiment 1 was designed to investigate the role of conscientiousness, task difficulty, and response awareness in response-related processing and associated ERP components using an Eriksen flanker task. A standard two-choice arrowhead version of a flanker task was chosen for Experiment 1 with task difficulty clearly defined as greater in the incongruent condition than the congruent condition (Eriksen & Eriksen, 1974). This task has often been used in the investigation of response-related processes; however investigation of the impact of task difficulty has not always been possible because few errors occur in the easier congruent condition (e.g., Scheffers & Coles, 2000). It was hypothesised that if, as Falkenstein (2004a) argued, ERN/Ne is reduced in difficult tasks, then ERN/Ne mean amplitude would be significantly more negative in congruent conditions compared to incongruent. If, on the other hand, as argued by Pailing and Segalowitz, (2004b) task difficulty has no impact on early response-related negativities then ERN/Ne and CRN amplitudes will not differ according to congruency levels.

Ashton and Lee (2001) suggest that trait conscientiousness may be a measure of active engagement in task-related behaviours. Indeed, they argue that this personality dimension may reflect the extent to which an individual will engage in behaviours that will enhance accuracy and task performance. Van Lieshout (2000) also suggests that conscientiousness influences executive regulation of goal-directed behaviour. As such, Experiment 1 included measures of conscientiousness alone. This provided a less complex measure of task salience, without the inclusion of external motivation in the form of incentives as was investigated by Pailing and Segalowitz (2004a). It was predicted that, if the ERN/Ne reflects the motivational

significance or salience of an error response, then those high in conscientiousness would elicit significantly higher ERN/Ne than CRN mean amplitudes. However, those with low levels of conscientiousness would show little or no difference in ERN/Ne and CRN amplitudes. Additionally, high conscientious participants were expected to elicit significantly larger ERN/Ne amplitudes than low conscientious individuals. Later response-related components have not specifically been investigated in terms of this personality trait and thus it is unclear how this variable may impact. However if, as Ridderinkhof et al. (2009) point out, the Pe reflects the motivational significance of an error then a similar outcome was expected in the early positive error-related component as that which was expected for the early error-related negative component.

The error-awareness hypothesis of Pe has had some empirical support. Initially this explanation was based on relating post-error slowing to conscious error recognition (Falkenstein et al., 2000), however a number of studies have provided experimental evidence that demonstrates post-error slowing in combination with Pe amplitude changes associated with subjective awareness of errors. Nieuwenhuis et al. (2001), using an anti-saccade task where participants were asked to indicate by button press if they made an error, found early Pe mean amplitude to be influenced by perception of error response whereas ERN/Ne was not. Endrass et al. (2005) also using an anti-saccade task, reported similar outcomes. Conversely, Endrass et al. (2007) found no differences in ERN/Ne and early Pe amplitudes related to perceived error awareness, however late Pe mean amplitude was larger for aware than unaware errors. Again, this outcome was derived from anti-saccade task data. Interestingly, in an earlier study, Scheffers and Coles (2000) using a flanker task demonstrated ERN/Ne amplitude differences according to perception of accuracy. Pe amplitude

was not investigated in this study. Taken together, these findings suggest a task-specific factor may be involved in the modulation of Pe amplitudes. At the time of designing and running the current experiment (2006) the majority of investigations of Pe and the error-awareness hypothesis had reported the use of anti-saccade tasks and some inconsistencies were evident. There was a clear need to expand the investigation of early and late Pe in terms of the error-awareness hypothesis beyond the ocular-motor field. Since this time, some investigators have indicated further support for the error-awareness hypothesis of Pe. Go/Nogo tasks, both visual and auditory, have produced outcomes that support the error-awareness hypothesis of the late Pe, with mean amplitudes reported to be larger for aware than unaware errors (O'Connell et al., 2007; Shalgi et al., 2009).

Awareness of responses was measured directly with the inclusion of a response awareness question, adapted from Scheffers and Coles (2000), following responses to stimuli on every trial. This was specifically included to investigate the error awareness hypothesis of Pe, with larger mean Pe amplitudes predicted to be associated with error responses when participants were aware compared to when they were not aware of their errors. However, the inclusion of this variable also provided a measure to investigate the combined effects of task demands and certainty of responses.

## **Method**

### **Participants**

Thirty nine female, right-handed participants, aged between 18 and 34 years (mean age = 20.87), were recruited from first year psychology students at the University of Tasmania. The study had ethical approval from the Human Research Ethics



Committee (Tasmania) Network. Age restrictions were included due to noted decreases in ERP component amplitudes with increasing age (Friedman, Boltri, Vaughan, & Erlenmyer-Kimling, 1985). Participants were screened according to a medical history questionnaire (see Appendix B). Those with a history of mental or neurological disorders as well as those who were users of tobacco, cannabis, or prescription medication were excluded as these have been reported to affect ERP components (Polich & Kok, 1995). Participation was restricted to females since sex differences in performance monitoring have been noted by researchers and this was not a focus of the current study (Larson, South, & Clayson, 2011). All participants reported normal or corrected to normal vision. Data from 23 participants were excluded because an insufficient number of error responses ( $< 20$ ) were made, leaving 16 participants with a mean age of 20.63 years whose data were included in analyses. The inclusion criterion of a minimum of 20 trials was based on the research of Cohen and Polich (1997) and Marco-Pallares, Cucurell, Münte, Strien, and Rodriguez-Fornells (2011) who have found that peak amplitudes are less stable with fewer than 20 trials included in the ERP averaging process. Participants were also grouped in relation to their levels of conscientiousness as measured by a self-administered personality test, the Revised NEO Personality Inventory (NEO PI-R) (Costa & McCrae, 1992). Those with scores on the conscientiousness scale of this test ranging from zero to 31 were considered to have low levels of conscientiousness ( $n = 6$ ) while those with scores of 32 and above were considered to have high levels of conscientiousness ( $n = 10$ ).

### **Apparatus and EEG recording**

The tasks were completed using Neuroscan Stim<sup>2</sup> software on a PC.

Electroencephalographic (EEG) data were recorded using a Neuroscan SynAmps<sup>2</sup>

system, SCAN 4.4 software and a 32 channel Aegis Array electrode cap with sintered Ag/AgCl electrodes.

EEG data were recorded from six midline (Fz, FCz, Cz, CPz, Pz, Oz) and 24 homologous scalp positions from both hemispheres (FP1/2, F3/4, F7/8, FT7/8, FC3/4, C3/4, T7/8, TP7/8, CP3/4, P3/4, P7/8, O1/2) using linked mastoids as the reference and an AFz ground. Impedances were maintained at 10k $\Omega$  or less. Data were sampled continuously at 1000Hz and amplified at 200Hz, with online band-pass filter parameters of .15Hz to 100 Hz. Continuous data were corrected for electro-oculographic (EOG) activity using the ocular artifact reduction algorithm developed by Compumedics Neuroscan (2006) and based on combined regression analysis and artifact averaging (Semlitsch, Anderer, Schuster, & Presslich, 1986). A 30Hz low-pass filter was applied to the data following acquisition. Average waveforms were computed for a 1000 ms epoch commencing 100 ms prior to response onset. Data were examined for artifacts and included in averages provided amplitude within the identified epoch did not exceed  $\pm 150 \mu\text{V}$ . Epochs of activity were then baseline corrected using the 100 ms pre-response time window

## **Stimuli**

Participants completed an arrowhead version of the flanker task (Eriksen & Eriksen, 1974). They were shown sets of five arrowheads (congruent <<<<<, >>>>>, incongruent >><>, <<<<<), and were instructed to indicate, on a response pad, the direction of the centre arrowhead. Congruent and incongruent arrowheads (probability 0.5) were presented randomly in 40 pt white font on a black background. A fixation cross was presented prior to the stimulus onset. The stimuli were presented for 200 ms with a 1500 ms response window. A response certainty screen immediately followed each trial response with the question “Did you make an

error?” appearing in the centre of the screen until a response was made. The participant had four response options: no - very sure; no - somewhat sure; yes - somewhat sure; yes - very sure. Those responses to the awareness question that fell into the somewhat sure categories were excluded from further analysis.

## **Procedure**

Participants attended the Cognitive Neuroscience Laboratory for a session totalling approximately two hours. Initially, participants were given an information sheet and consent form to complete (see Appendices E and F). They then completed the medical screening questionnaire and the Edinburgh Inventory (Oldfield, 1971) to assess handedness (see Appendix G). This was followed by the completion a self-administered personality test, the NEO PI-R (Costa & McCrae, 1992). Participants were then fitted with an electrode cap and completed the two computer-administered tasks in a sound attenuated room. The tasks were explained and opportunity for practice given before presentation of trials. The task was presented in 12 counterbalanced blocks of 48 trials and participants were instructed to respond as quickly and accurately as possible. Rest periods followed each block of trials to prevent fatigue. The time taken to complete the task ranged between 45 minutes to one hour, depending on the time taken for rest periods.

## **Design**

This experiment followed a 2 [Conscientiousness: high, low]  $\times$  2 (Response Type: error, correct)  $\times$  2 (Congruency: congruent, incongruent)  $\times$  2 (Response Awareness: aware, unaware)  $\times$  5 (Sagittal Site: Fz, FCz, Cz, CPz, Pz) mixed design. The ERP dependent measures were ERN/Ne, CRN, early and late Pe and Pc mean amplitude

and the behavioural dependent measures were reaction time and accuracy of responses to congruent and incongruent stimuli.

## **Analyses**

A series of two-, three- and four-way mixed measures ANOVAs were used to examine behavioural data and early and late response-related negativities and positivities for Experiment 1. Reaction time to error and correct responses and accuracy were analysed using a 2 [Conscientiousness: high, low]  $\times$  2 (Congruency: congruent, incongruent)  $\times$  2 (Response Type: correct, error) mixed measures ANOVA.

Theories of response-monitoring suggest that the early ERP correlates of responses are, in the main, representations of evaluative processes (Falkenstein et al., 1990; Holroyd & Coles, 2002; Yeung et al., 2004). However, there is not agreement on how, and if, these processes differ in terms of correct and error responses. The focus of current theories has been on error-related activity with less emphasis placed on explaining negative activity associated with correct responses. Indeed, Holroyd and Coles' (2002) reinforcement-learning hypothesis fails to mention or explain the CRN. The mismatch hypothesis, proposed by Falkenstein et al. (1990), suggests a comparative process results in a negative deflection representative of an evaluation of actual and required responses. Similarly, the conflict monitoring hypothesis provides an explanation of response monitoring in terms of conflict between possible correct and incorrect responses (Yeung et al., 2004). However, it was not until Yeung et al. considered error and correct-related data separately that they were able to discern differing levels on conflict associated with characteristics of flanker stimuli in error responses. Theories of response-related positivities have also focussed on activity associated with errors (Overbeek et al. 2005) with consideration and

explanations of the ERP correlates of late correct-related positivities in the minority and only beginning to emerge in the literature (Burgio-Murphy et al., 2007).

A large body of evidence suggests that, as Holroyd and Coles (2002) demonstrated, response related processes differ for correct and error responses. ERN/Ne and CRN amplitudes have been found to be impacted differentially by age (e.g., Davies et al., 2004; Santesso et al., 2006). The dissociability of the ERN/Ne and Pe has also been demonstrated across a number of experimental paradigms (e.g., Albrecht et al., 2008; Davies et al., 2004; Falkenstein et al., 2005; Ladouceur et al., 2007; Overbeek et al., 2005), with Arbel & Donchin, (2009) further confirming the dissociability of these components by demonstrating topographically separate components.

Consistent with past researchers (e.g., Hajcak et al., 2005; Scheffers & Coles, 2000), overall differences between error and correct response-related mean amplitude were determined using a  $2$  [Conscientiousness: high, low]  $\times$   $2$  (Congruency: congruent, incongruent)  $\times$   $2$  (Response Type: correct, error)  $\times$   $2$  (Sagittal Site: Fz, FCz or CPz, Pz) mixed measures ANOVA. In each case the sagittal variables were selected to reflect differing topography associated with early or late response-related activity. Since theoretical explanations and research evidence suggests that response-related components are dissociable a second-level analysis was conducted on each component (ERN/Ne, CRN, early and late Pe and Pc) separately

A further analysis was conducted on response-related data including a within subject's variable (Response Awareness: aware, unaware). Analysis was confined to activity from participants who correctly ( $n=5$ ) and incorrectly ( $n=6$ ) responded to incongruent stimuli only since there were insufficient participants who were unaware

of their responses in the congruent condition. There were also insufficient trials to match correct and incorrect trials in both aware and unaware conditions for each participant, so Response Type was considered a between subjects variable for this analysis. The between subjects variable Conscientiousness was also excluded from this analysis because there were not enough high conscientious participants to create high and low conscientious groups within this sample. Thus electrophysiological measures, in terms of response awareness, were examined using a 2 [Response Type: correct, error]  $\times$  2 (Response Awareness: aware, unaware)  $\times$  2 (Sagittal Site: Fz, FCz or CPz, Pz) mixed measures ANOVA and behavioural measures, using 2 [Response Type: correct, error]  $\times$  2 (Response Awareness: aware, unaware) mixed measures ANOVA.

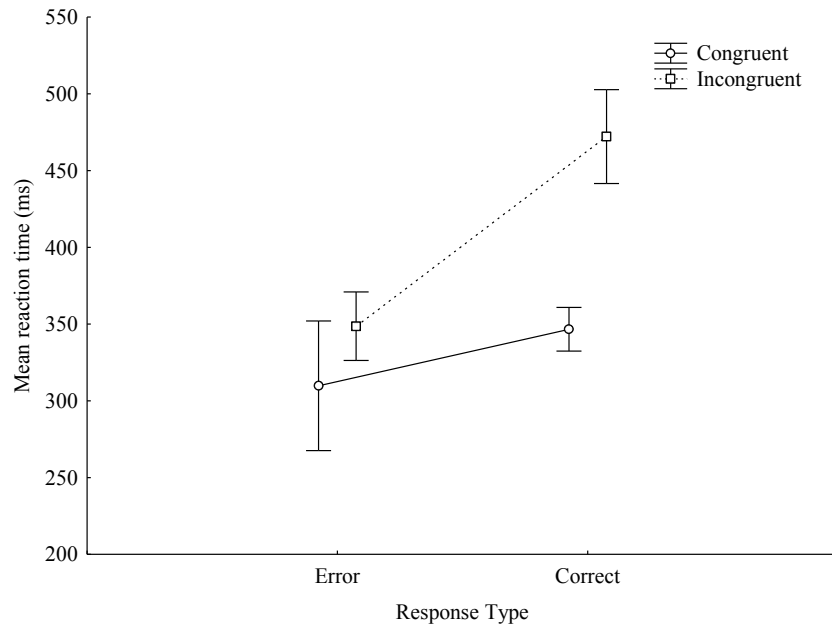
All significance levels were maintained at  $p < .05$  and Tukey HSD post hoc tests were used to test for significant differences between individual means where appropriate. Data from participants were included for analysis providing 20 or more correct and error responses were made in each experimental condition.

## Results

### Behavioural Analyses

The three-way ANOVA conducted on reaction time data revealed a significant main effect of Response Type,  $F(1, 14) = 78.62$ ,  $MSE = 1226$ ,  $p < .001$ ,  $\eta^2 = .85$ , and a significant main effect of Congruency,  $F(1, 14) = 71.93$ ,  $MSE = 1409$ ,  $p < .001$ ,  $\eta^2 = .84$ , which were modified by a significant Response Type  $\times$  Congruency interaction,  $F(1, 14) = 17.37$ ,  $MSE = 1623$ ,  $p < .001$ ,  $\eta^2 = .55$  (see Figure 1). Tukey post hoc tests showed that mean reaction time was significantly slower for responses to incongruent stimuli than to congruent stimuli ( $ps < .05$ ). Error responses were significantly faster than correct responses in the incongruent condition ( $p < .001$ )

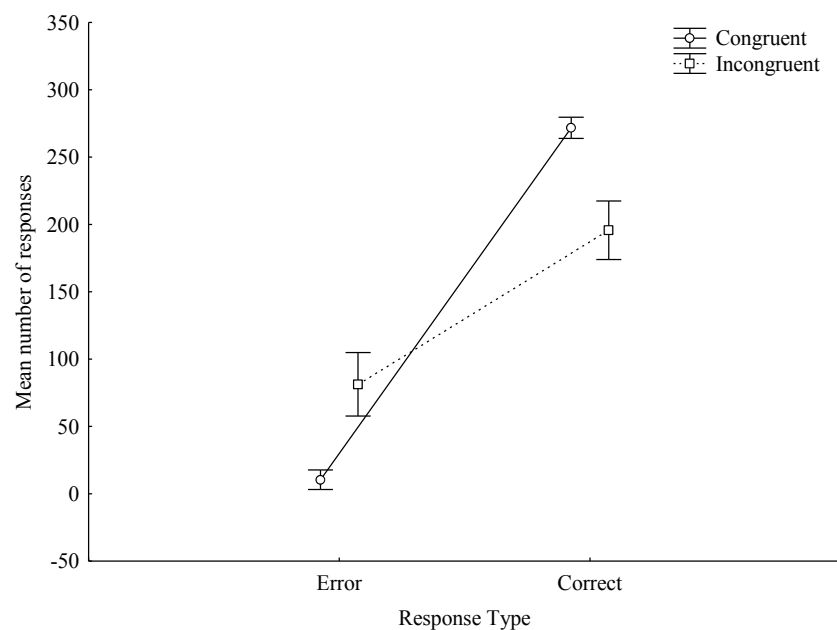
however in the congruent condition reaction times to correct and error responses were not significantly different ( $p > .05$ ). In terms of reaction time, no significant main effect or interactions involving Conscientiousness were evident.



*Figure 1.* Mean reaction time (ms) for error and correct responses to congruent and incongruent stimuli (vertical bars denote 0.95 confidence intervals).

Error rates ranged from 6% to 36% across participants with a mean error rate of 16.01%. The three-way ANOVA completed on accuracy data revealed a significant main effect of Response Type,  $F(1,14) = 198.5$ ,  $MSE = 2667$ ,  $p < .001$ ,  $\eta^2 = .93$ , indicating that overall there were significantly more correct responses than error responses, and a significant main effect of Congruency,  $F(1, 14) = 13.14$ ,  $MSE = 8$ ,  $p < .001$ ,  $\eta^2 = .48$ , indicating that overall more responses were made to congruent stimuli than incongruent stimuli. These effects were modified by a significant Response Type  $\times$  Congruency interaction,  $F(1, 14) = 80.76$ ,  $MSE = 1003$ ,  $p = .002$ ,  $\eta^2 = .85$  (see Figure 2). Consistent with past research (e.g., Hajcak et al.,

2005; Pailing & Segalowitz, 2004a, 2004b) and as shown in Figure 2 and confirmed by Tukey post hoc analyses, there were significantly more correct responses to congruent stimuli than incongruent ( $p < .001$ ) but significantly more error responses to incongruent stimuli than congruent stimuli ( $p < .001$ ). Again, analysis of accuracy data did not show significant effects involving Conscientiousness.

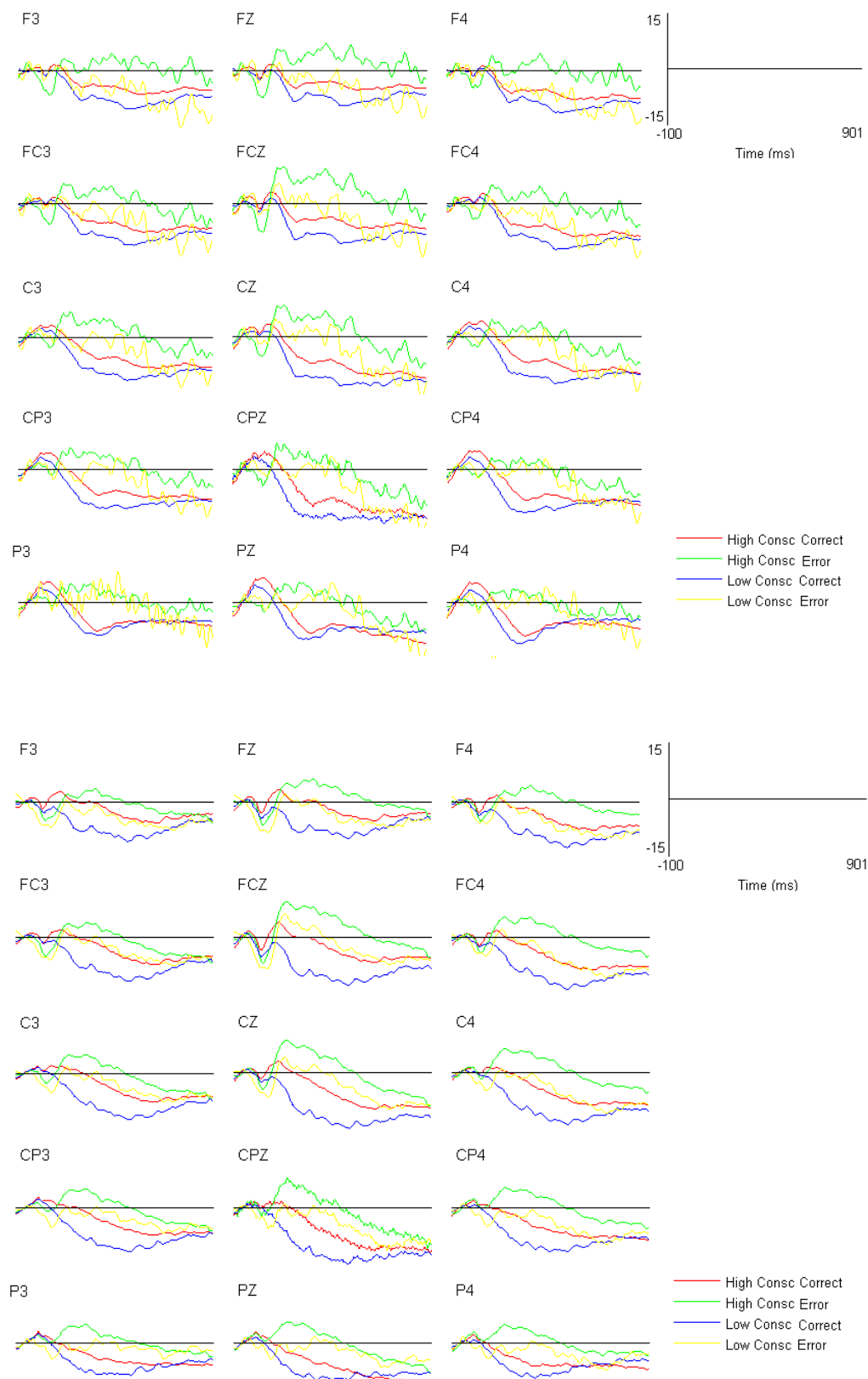


*Figure 2.* Mean number of error and correct responses to congruent and incongruent stimuli (vertical bars denote 0.95 confidence intervals).

### **Grand Mean Averages**

Perusal of grand mean averages confirmed that ERN/Ne and CRN were maximal at frontal, and fronto-central midline sites (see Figure 3).





*Figure 3.* Grand mean average waveforms for high and low conscientious participants for error and correct responses in congruent (top panel) and incongruent (bottom panel) conditions.

This is similar to the findings of other researchers (e.g., Falkenstein et al., 1991; Falkenstein et al., 2000; Gehring et al., 1993; Hajcak et al., 2004; Yeung et al., 2004). As can be seen in Figure 3, ERN/Ne and CRN occur approximately 50 ms post response. This guided choice of the epoch from which mean amplitude for this component was measured (0 – 100 ms post response). This time frame is also in accordance with some past research in the area (Hajcak et al., 2005; Hajcak et al., 2004; Hajcak & Simons, 2008).

Early positive activity was also noted frontally, with a clear separation of activity associated with correct and error responses. An early positive peak occurred approximately 100 ms post correct responses and a further peak approximately 150 ms associated with error responses. This guided the choice of measurement window for the early correct response-related positivity (50 – 200 ms post response) and the early error response-related positivity (120 – 250 ms). The correct response-related positivity displayed a clear reduction in amplitude compared to the error response-related positivity.

Perusal of the grand mean averages revealed a slow going wave at parietal sites that was also maximal at the midline. Similar to the early positive activity there was a clear delineation between correct and error related activity. The epoch chosen to measure this activity was 300 – 600 ms post response. This choice was guided by the grand means since past researchers have used a range of time windows and quantification methods (e.g., Band & Kok, 2000; Falkenstein et al., 2005; Hajcak et al., 2004; Mathalon et al., 2002; Ruchow et al., 2005; Shalgi et al., 2009).

### **Electrophysiological Analyses**

To determine whether error and correct response-related activity were significantly different, a comparison of mean amplitude was completed for ERN/Ne and CRN,

early Pe and Pc, and late Pe and Pc. In each case, error-related activity was significantly different from correct-related activity ( $ps < .05$ ).

A four-way ANOVA conducted on ERN/Ne and CRN mean amplitude data indicated that ERN/Ne mean amplitude ( $M = -3.86$ ,  $SE = 1.42$ ) was significantly larger than CRN mean amplitude ( $M = -0.95$ ,  $SE = 0.77$ ),  $F(1, 14) = 6.31$ ,  $MSE = 40.32$ ,  $p = .02$ ,  $\eta^2 = .31$ .

The four-way ANOVA conducted on early Pe and Pc mean amplitude data revealed a significant main effect of Response Type,  $F(1, 14) = 20.24$ ,  $MSE = 26.66$ ,  $p < .001$ ,  $\eta^2 = .59$ , which was modified by a significant Response Type  $\times$  Sagittal Site interaction,  $F(1, 14) = 30.33$ ,  $MSE = 2.01$ ,  $p < .001$ ,  $\eta^2 = .68$  (see Figure 4).

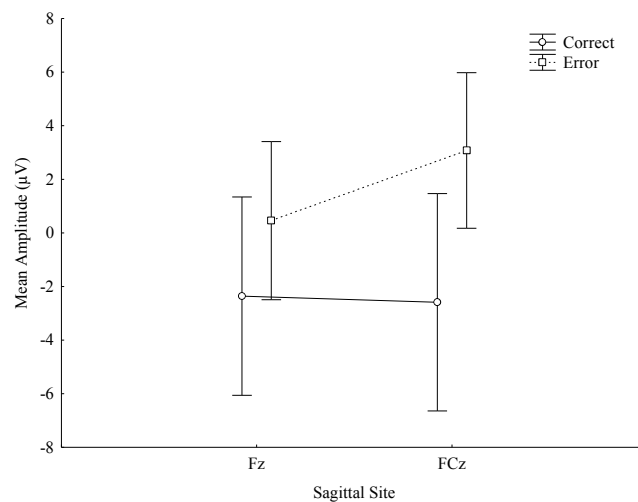


Figure 4. Early Pe and Pc mean amplitude at Fz and FCz (vertical bars denote 0.95 confidence intervals).

As can be seen in Figure 4, and confirmed by Tukey post hoc tests Pc mean amplitude was significantly larger at FCz than Fz ( $p < .001$ ) however there was no significant difference between Pe mean amplitude at these sites ( $p > .05$ ). Overall early Pe was significantly more positive than early Pc mean amplitude but this was more pronounced at FCz ( $p < .001$ ) compared to Fz ( $p < .001$ ).

The four-way ANOVA performed on late Pe and Pc mean amplitude data revealed a significant main effect of Response Type,  $F(1, 14) = 57.83$ ,  $MSE = 35.18$ ,  $p < .001$ ,  $\eta^2 = .81$ , a significant Response Type  $\times$  Sagittal Site interaction,  $F(1, 14) = 14.48$ ,  $MSE = 1.69$ ,  $p = .002$ ,  $\eta^2 = .51$ , which were modified by a Response Type  $\times$  Congruency  $\times$  Sagittal Site interaction,  $F(1, 14) = 5.14$ ,  $MSE = 0.79$ ,  $p = .04$ ,  $\eta^2 = .27$ . As shown in Figure 5, and confirmed by separate 2 (Response Type: correct, error)  $\times$  2 (Congruency: congruent, incongruent) repeated measures ANOVAs at each Sagittal Site, mean amplitude elicited by error responses at CPz ( $F(1, 15) = 65.18$ ,  $MSE = 19.79$ ,  $p < .001$ ,  $\eta^2 = .81$ ) and Pz ( $F(1, 15) = 56.34$ ,  $MSE = 15.06$ ,  $p < .001$ ,  $\eta^2 = .79$ ) was significantly more positive than mean amplitude elicited by correct responses.

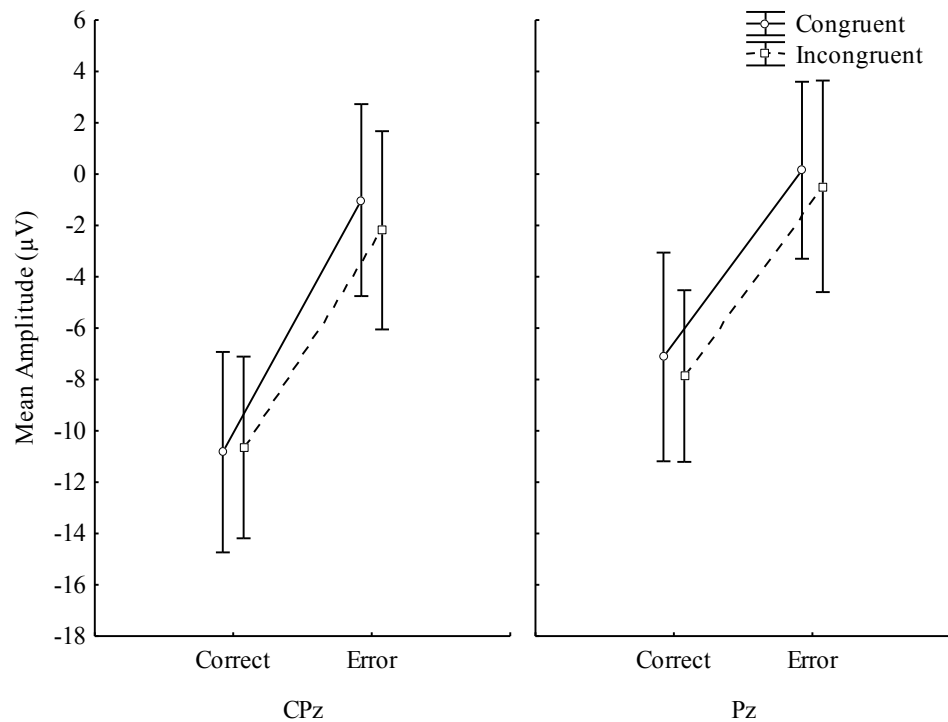


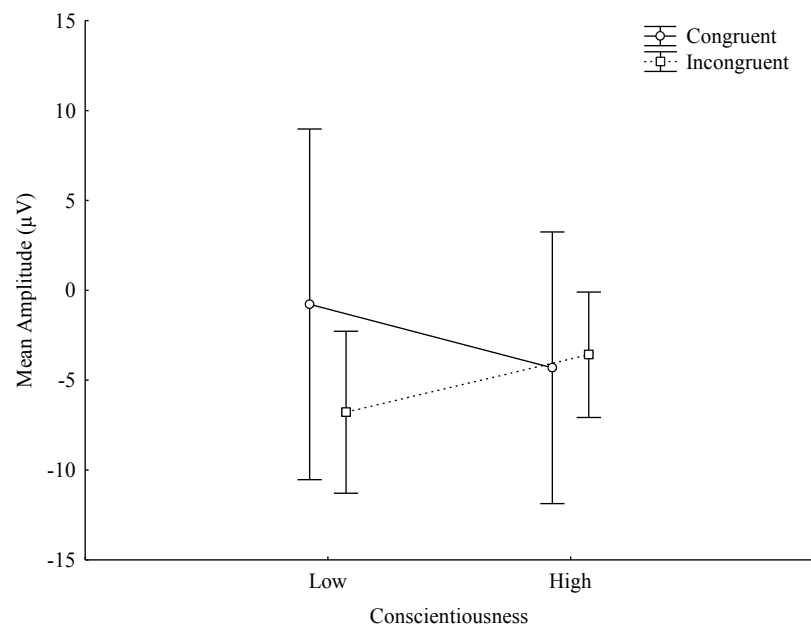
Figure 5. Late Pe and Pc mean amplitude to congruent and incongruent stimuli at CPz and Pz (vertical bars denote 0.95 confidence intervals).

Although no other comparisons between means reached significance in either analysis, Figure 5 shows that at CPz, there was a larger difference between responses to congruent and incongruent stimuli for error responses than for correct responses, whereas at Pz there was little differentiation between responses to incongruent and congruent stimuli for correct or incorrect responses. No other main effects or interactions in this analysis reached significance.

Separate analyses of each response-related component (ERN/Ne, CRN and early and late Pe and Pc) were undertaken and are presented below.

### ERN/Ne

The three-way ANOVA conducted on ERN/Ne mean amplitude data revealed a significant Congruency  $\times$  Conscientiousness interaction,  $F(1, 14) = 5.65$ ,  $MSE = 30.05$ ,  $p = .03$ ,  $\eta^2 = .29$  (see Figure 6).



*Figure 6.* ERN/Ne mean amplitude to congruent and incongruent stimuli for low and high conscientious groups (vertical bars denote 0.95 confidence intervals).

Tukey post hoc tests indicated that there were no significant differences between individual means ( $ps > .05$ ), however Figure 6 shows that there was little difference in mean ERN/Ne amplitude to congruent and incongruent stimuli for high conscientious participants yet low conscientious individuals showed larger mean ERN/Ne negativity in the incongruent compared to the congruent condition. Whereas in the incongruent condition low conscientious participants displayed larger mean ERN/Ne negativity than high conscientious participants, in the congruent condition an opposite pattern emerged – high conscientious participants displaying larger mean ERN/Ne negativity than low conscientious participants. No other main effects or interactions reached significance.

### CRN

The three-way ANOVA conducted on CRN mean amplitude data revealed a significant Congruency  $\times$  Sagittal Site interaction,  $F(1, 14) = 17.48$ ,  $MSE = 0.22$ ,  $p < .001$ ,  $\eta p^2 = .56$  (see Figure 7).

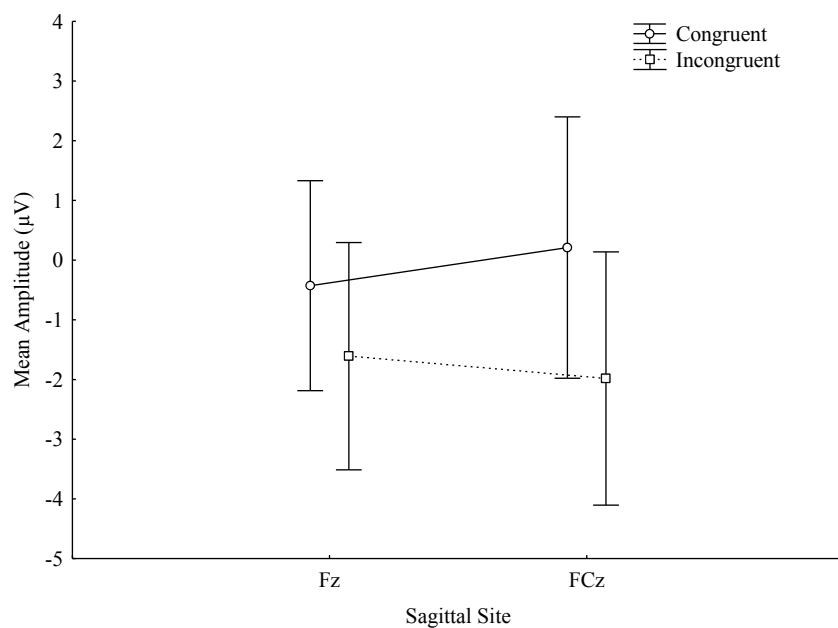


Figure 7. CRN mean amplitude to congruent and incongruent stimuli at Fz and FCz (vertical bars denote 0.95 confidence intervals).

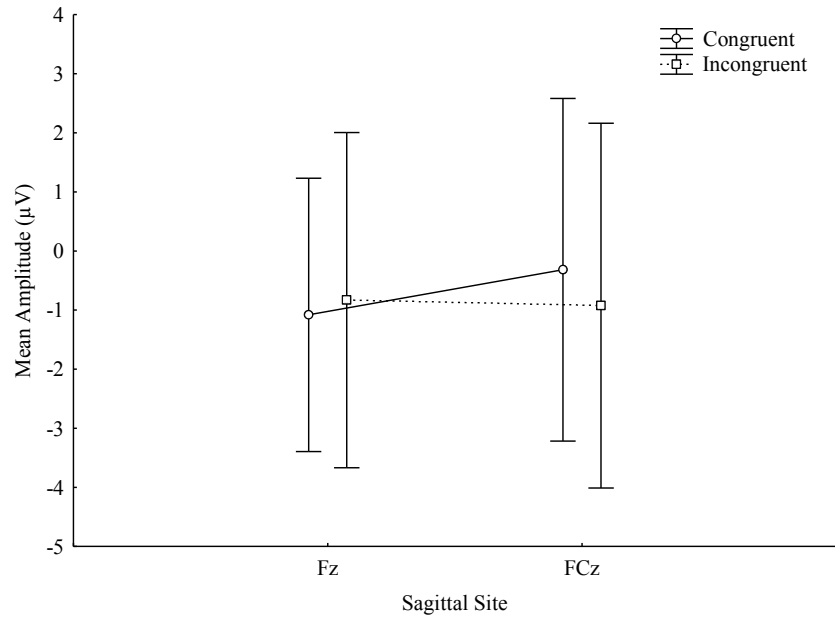
Tukey post hoc tests showed that at both FCz and Fz mean CRN amplitude to incongruent stimuli was significantly more negative than that elicited by congruent stimuli and this difference was larger at FCz ( $p < .01$ ) compared to Fz ( $p < .001$ ). No other main effects or interactions reached significance

### **Early Pe**

The three-way ANOVA conducted on the early Pe data revealed that overall early Pe mean amplitude shown by high conscientious participants ( $M = 5.79$ ,  $SE = 1.25$ ) was significantly more positive than that shown by low conscientious participants ( $M = 1.42$ ,  $SE = 1.61$ ),  $F(1, 14) = 4.61$ ,  $MSE = 62.26$ ,  $p = .04$ ,  $\eta^2 = .25$ . Early Pe mean amplitude was significantly more positive at FCz ( $M = 5.42$ ,  $SE = 1.08$ ) than Fz ( $M = 1.79$ ,  $SE = 1.03$ ),  $F(1, 14) = 40.17$ ,  $MSE = 4.90$ ,  $p < .001$ ,  $\eta^2 = .74$ . No other main effects or interactions reached significance in this analysis.

### **Early Pc**

The three-way ANOVA conducted on early Pc mean amplitude data revealed a significant Congruency  $\times$  Sagittal Site interaction,  $F(1, 14) = 11.35$ ,  $MSE = 0.24$ ,  $p = .004$ ,  $\eta^2 = .45$  (see Figure 8).



*Figure 8.* Early Pc mean amplitude to congruent and incongruent stimuli at Fz and FCz (vertical bars denote 0.95 confidence intervals).

Post hoc tests indicated that early Pc mean amplitude to both congruent and incongruent stimuli at FCz was significantly more positive than mean amplitude to congruent stimuli at Fz ( $p < .05$ ). However there were no significant differences in early Pc mean amplitude according to levels of congruency at Fz ( $p > .05$ ), or for early Pc mean amplitude elicited by incongruent stimuli across Fz and FCz ( $p > .05$ ). No other main effects or interactions reached significance.

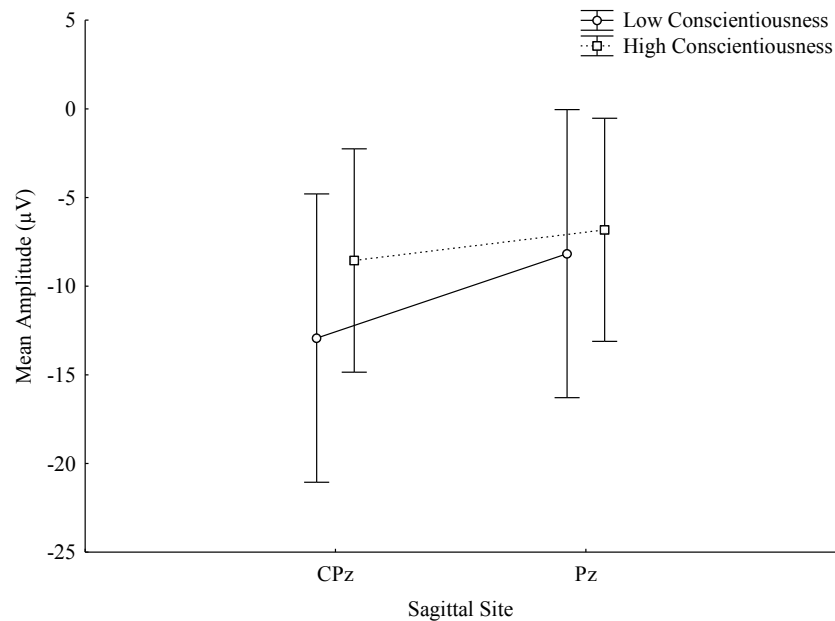
### **Late Pe**

The three-way ANOVA conducted on late Pe data revealed that mean amplitude tended to be more positive at Pz ( $M = -0.16$ ,  $SE = 1.62$ ) than at CPz ( $M = -1.60$ ,  $SE = 1.57$ ),  $F(1, 14) = 3.95$ ,  $MSE = 7.86$ ,  $p = .07$ ,  $\eta p^2 = .22$ . No other main effects or interactions reached significance.



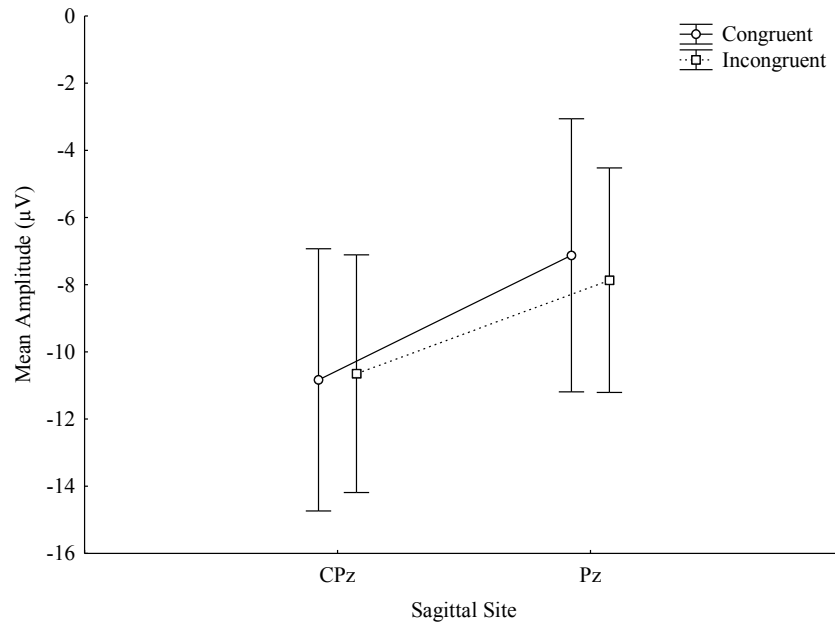
### Late Pc

The three-way ANOVA performed on late Pc mean amplitude data revealed a significant main effect of Sagittal Site,  $F(1, 14) = 29.24$ ,  $MSE = 5.41$ ,  $p < .001$ ,  $\eta p^2 = .68$  which was qualified by two higher order interactions. Firstly, there was a significant Sagittal Site  $\times$  Conscientiousness interaction,  $F(1, 14) = 6.36$ ,  $MSE = 5.41$ ,  $p = .02$ ,  $\eta p^2 = .31$  (see Figure 9). Tukey post hoc tests revealed that low conscientious participants demonstrated significantly more positive late Pc mean amplitude at Pz compared to CPz ( $p < .01$ ). While other comparisons did not reveal any significant differences between individual means, Figure 9 shows that late Pc mean amplitude was more positive for high conscientious than low conscientious participants at both CPz and Pz this difference was largest at CPz.



*Figure 9.* Late Pc mean amplitude for high and low conscientious participants at CPz and Pz (vertical bars denote 0.95 confidence intervals).

Secondly, a significant Congruency  $\times$  Sagittal Site interaction was evident,  $F(1, 14) = 7.31$ ,  $MSE = 0.44$ ,  $p = .02$ ,  $\eta p^2 = .34$  (see Figure 10).



*Figure 10.* Late Pc mean amplitude to congruent and incongruent stimuli at CPz and Pz (vertical bars denote 0.95 confidence intervals).

Tukey post hoc tests revealed that late Pc mean amplitude elicited by both congruent and incongruent stimuli was significantly more positive at Pz than at CPz ( $ps < .001$ ). While no other comparison of individual means reached significance ( $ps > .05$ ), as can be seen in Figure 10 late Pc mean amplitude differences between amplitudes elicited by congruent and incongruent stimuli were larger at Pz compared to CPz.

### **Response Awareness**

The examination of response awareness and its impact on response-related components is presented below. These analyses were based on activity elicited by responses to incongruent stimuli only since there were insufficient responses where participants were unaware of their responses to congruent stimuli. An examination of

the impact of conscientiousness within this analysis was also not possible because there were not enough high conscientious participants to create high and low conscientious groups within this sample.

### **Behavioural analyses**

The two-way ANOVA conducted on reaction time data within aware and unaware responses showed that mean reaction time for error responses was significantly faster ( $M = 317.03$ ,  $SE = 13.76$ ) than for correct responses ( $M = 453.91$ ,  $SE = 15.07$ ,  $F(1, 9) = 45.00$ ,  $MSE = 2271$ ,  $p < .001$ ,  $\eta^2 = .83$ ). The three-way ANOVA conducted on accuracy data showed that there were significantly more correct responses ( $M = 94.7$ ,  $SE = 10.15$ ) than error responses ( $M = 49.25$ ,  $SE = 9.27$ ),  $F(1, 9) = 10.93$ ,  $MSE = 1031$ ,  $p = .009$ ,  $\eta^2 = .55$  and that participants were unaware of significantly more responses ( $M = 85.07$ ,  $SE = 7.80$ ) than they were aware ( $M = 58.88$ ,  $SE = 7.71$ ),  $F(1, 9) = 13.24$ ,  $MSE = 282.5$ ,  $p = .005$ ,  $\eta^2 = .60$ . No other main effects or interactions reached significance for either reaction time or accuracy data.

### **Grand mean averages**

Grand mean average waveforms were obtained for correct and incorrect responses in the incongruent condition only, and these were broken down by levels of participant awareness to their response (aware/unaware). Figure 11 shows, as with the overall grand means, a clear negative deflection occurring early post response (approximately 50 ms). This is followed by an early positive deflection that again delineates correct and incorrect responses. A later slow going wave is also evident although there appears little difference as the activity is considered frontally through to parietal regions.

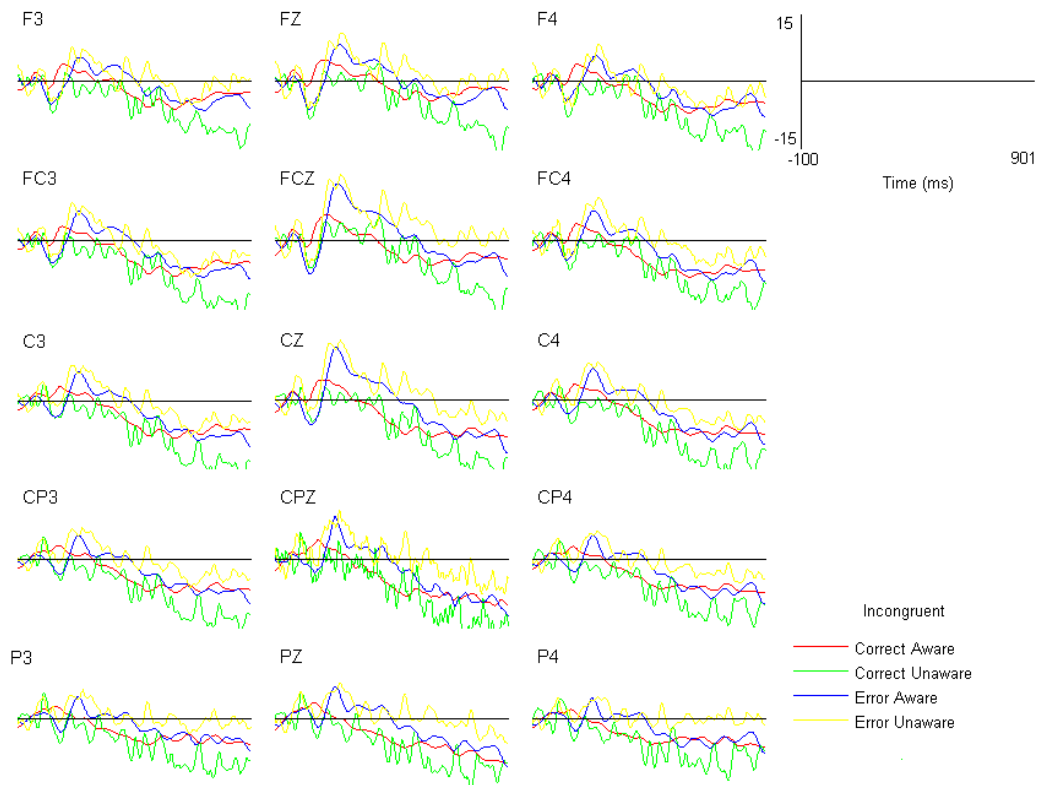


Figure 11. Grand mean average waveforms for error and correct responses to incongruent stimuli when participants were aware and unaware of their responses.

### Electrophysiological analyses

The three-way ANOVA conducted on data in terms of response awareness revealed no significant differences between error and correct response-related activity for any early or late component ( $ps > .05$ ). When error and correct response-related components were analysed separately ERN/Ne, CRN, early Pc and late Pc showed no significant main effects or interactions. Early Pe was shown to be focused at FCz ( $M = 3.22$ ,  $SE = 1.98$ ) compared to Fz ( $M = 0.70$ ,  $SE = 1.54$ ),  $F(1, 5) = 5.92$ ,  $MSE = 6.40$ ,  $p = .06$ ,  $\eta^2 = .54$  and late Pe was most prominent at Pz ( $M = 0.81$ ,  $SE = 3.65$ ) compared to CPz ( $M = -1.48$ ,  $SE = 4.02$ ,  $F(1, 5) = 5.91$ ,  $MSE = 5.33$ ,  $p = .06$ ,  $\eta^2 = .54$ ). The topographical distribution of these components is similar to that

found by a number of previous researchers (e.g., Endrass et al., 2007; Hajcak et al., 2004; Ruchow et al., 2005).

## **Discussion**

Overall, error responses were found to produce significantly larger mean amplitude than correct responses. The prediction that task demands and levels of conscientiousness would be reflected in differential ERN/Ne and CRN amplitudes differences was not supported. Conscientiousness levels were found to moderate congruency effects for errors only within the early time windows, thus partially supporting predicted outcomes. The hypothesis regarding Pe as a reflection of conscious error awareness was also not supported.

ERN/Ne mean amplitude was significantly more negative than CRN and error responses elicited significantly larger positive amplitudes than correct responses in later components. These findings are in accordance with a large body of research investigating response-related processes and can be explained within existing theories of the ERN/Ne. Such findings provide support for an explanation of both the ERN/Ne and CRN components as representative of a response-evaluation process. Specifically, amplitude differences in negative components occur as a result of a comparative process that occurs between correct and error responses (Falkenstein et al., 1990; Suchan et al., 2007; Vidal et al., 2000).

The data provided support for the argument that measures of underlying personality traits that may influence goal-directed behaviour, particularly conscientiousness, are a worthwhile inclusion in explanations of response-related processes. Congruency effects moderated by conscientiousness levels were apparent in ERN/Ne but not CRN. Specifically, no significant difference in mean ERN/Ne

amplitudes according to congruency was found for high conscientious participants, whereas errors to incongruent stimuli elicited significantly larger mean amplitudes than to congruent stimuli for low conscientious participants. Ashton and Lee (2001) provide a framework within which these outcomes can be explained. If, as they argue, conscientiousness reflects the degree to which individuals will engage in behaviours that will enhance accuracy and task performance then it follows that highly conscientious individuals may evaluate all errors similarly, irrespective of task difficulty, whereas low conscientious individuals may engage in evaluative processes according to task demands and this is reflected in differentiation of ERN/Ne amplitudes. Evidence that the impact of conscientiousness was evident for error responses only is consistent with the findings of Hajcak et al. (2005) who found incentive manipulations to impact amplitudes of ERN/Ne and not CRN and adds weight to the argument that the ERN/Ne is functionally separable from the CRN,

Conscientiousness effects were also evident in the early Pe with highly conscientious individuals displaying larger mean amplitudes than individuals with lower levels of conscientiousness. Such results may be reflective of the salience of errors, since highly conscientious individuals may be maximally engaged in tasks and regulation of goal-directed behaviour and thus impacted to a greater degree by errors than those individuals with low conscientiousness levels (Ashton & Lee, 2001; Pailing & Segalowitz, 2004a; Van Lieshout, 2000). This explanation of Pe is consistent with evidence put forward by Ridderinkhof et al. (2009) who have demonstrated that the Pe possesses similar properties to that of a P3 and have argued that the Pe, like the P3, reflects the conscious processing of motivationally significant events: in the case of Pe, motivationally salient errors.

Evidence of congruency effects in error and correct response-related components suggests that, contrary to Pailing and Segalowitz's (2004b) findings, task difficulty does in fact play a role in response evaluation processes. Significantly larger CRN mean amplitude to incongruent stimuli compared to congruent stimuli reflects differential evaluation of correct responses according to task demands. This is consistent with behavioural data that reflects greater reaction time and high error rates in the more demanding incongruent condition. Why this overall effect was evident in correct responses only and moderated by levels of conscientiousness in error responses remains unclear; however, again this suggests some functional separation of ERN/Ne and CRN and of early Pe and Pc.

The investigation of response awareness and its impact on response-related ERP components was an important aim of this series of experiments, and was included as a means to investigate response certainty in more specific detail and its interactive effects with task demands. This was, however, not feasible since there were insufficient unaware correct responses in congruent conditions to create workable averages. Overall analyses indicated no significant mean amplitude differences in terms of response awareness in early or late response-related components during the completion of incongruent flanker tasks. This suggests that response awareness does not play a role in response-related processes, or may be related to task demands, and indicates that Pe may in fact not provide a measure of response awareness as has been argued by a number of researchers (Endrass et al., 2005; Endrass et al., 2007; Nieuwenhuis et al., 2001). This interpretation should be considered cautiously since these findings are limited by small sample sizes.

Overall, the outcomes of Experiment 1 suggest that the ERP components said to represent response monitoring and evaluative processes reflect a more complex

process than simple error detection. It is more likely that task demands and individual differences interact to moderate these processes. The role of individual differences, namely conscientiousness, in response-related processes was further substantiated, although evidence suggests an interplay exists between task demands and underlying personality traits. In addition, confirmation of response certainty by direct measurement of response awareness across differing levels of task demands did not occur in Experiment 1. Consequently, the aim of Experiment 2 was to explore further the role of task demands, conscientiousness and response awareness within a standard arrowhead four-choice flanker task. This allowed for an evaluation of the impact of these factors within experiments where stimulus properties were identical but information processing demands were greater in the four-choice compared to the two-choice flanker task.



## **Chapter 6**

### **Experiment 2:**

#### **Response-related Processes and the Influence of Conscientiousness, Task Difficulty and Response Awareness: Evidence from a Four-choice Flanker Task**

The results of Experiment 1 suggested that trait conscientiousness levels and task demands interact to modulate response-related components that are said to reflect response monitoring and evaluation. Whereas explanations of the ERN/Ne provide a sound framework for understanding response-related processes at a basic level (Falkenstein et al., 1991), the impact of individual differences and task-specific factors are not specifically accounted for within current theories. Experiment 2 was designed to investigate the impact of increasing task demands using a four-choice flanker task, conscientiousness and response awareness on response-related components.

An overall increase in difficulty of the standard arrowhead flanker task used in Experiment 1 was achieved by using identical stimuli to that task but requiring a more complex decision relating to those stimuli. This provided an avenue to explore specifically how differential task demands in a more difficult task might impact the separate and combined effects of response awareness and conscientiousness on response-related processes. Consistent with the findings of Experiment 1, overall error response-related activity was expected to be significantly larger than correct response-related activity for early negative early positive and late positive components. The conscientiousness effects evident in Experiment 1 are consistent with the findings of a number of researchers who suggest that the motivational importance or salience of responses and underlying personality traits are

fundamentally involved in response monitoring and evaluation (Hajcak et al., 2005; Pailing & Segalowitz, 2004a). Evidence from Experiment 1 indicates that task demands are likely to moderate this effect. Consequently, further examination of the impact of differing conscientiousness levels in a more demanding task was included in Experiment 2 to further clarify this effect. Consistent with explanations of error-related components being linked to motivational factors (Hajcak et al., 2005; Pailing & Segalowitz, 2004a), it was expected that variation according to conscientiousness would be evident in ERN/Ne and Pe effects only. Also, if task demands moderate motivational effects then it was predicted that, similar to effects found in Experiment 1, mean ERN/Ne would not be differentiated in terms of levels of congruency for high conscientiousness levels, whereas low conscientiousness participants would demonstrate larger mean ERN/Ne in incongruent conditions compared to congruent conditions. On the other hand, if the four-choice flanker task proved too demanding in the incongruent condition then differentiation of ERN/Ne may also become evident for high conscientious individuals in this condition.

As with Experiment 1, certainty of responses was measured directly, with the inclusion of a response awareness question in the task following responses to stimuli. This was again also included to investigate the error awareness hypothesis of Pe (Endrass et al., 2005; Endrass et al., 2007; Nieuwenhuis et al., 2001), with larger mean Pe amplitudes predicted to be associated with error responses when participants were aware compared to when they were not aware of their errors.

## **Method**

### **Participants**

Twenty-one female, right-handed participants, aged between 18 and 33 years (mean

age = 20.29), were recruited from first year psychology students at the University of Tasmania. Participant exclusion criteria were similar to that outlined in Experiment 1. Data from two participants were excluded because an insufficient number of error responses were made, leaving 19 participants with a mean age of 20.47 years whose data were included in analyses. Participants were grouped according to conscientiousness scores the NEO PI-R (Costa & McCrae, 1992) as per Experiment 1 with group numbers totalling: low conscientiousness ( $n = 11$ ), and high conscientiousness ( $n = 8$ ).

### **Apparatus and ERP Recording**

The tasks were completed and data collected using the same software and equipment as that used in Experiment 1.

### **Stimuli**

Participants completed the same arrowhead version of the flanker task (Eriksen & Eriksen, 1974) as that used in Experiment 1 except that in this instance, participants were required to respond in terms of four alternate choices. They were instructed to indicate, on a four button response pad, the direction and congruency of the centre arrowhead.

### **Procedure**

The procedure for Experiment 2 followed that of Experiment 1.

### **Design and Analysis**

The design and analyses used in Experiment 2 were the same as that used in Experiment 1. As with Experiment 1 the analysis of data associated with response awareness was confined to error ( $n = 9$ ) and correct ( $n = 3$ ) related activity associated with incongruent stimuli only since there were insufficient participants who were

unaware of their responses in the congruent condition. There were also insufficient trials to match correct and incorrect trials in both aware and unaware conditions for each participant, so Response Type was considered a between subjects variable for this analysis. The between subjects variable Conscientiousness was also excluded from this analysis because there were not enough high conscientious participants to create high and low conscientious groups within this sample.

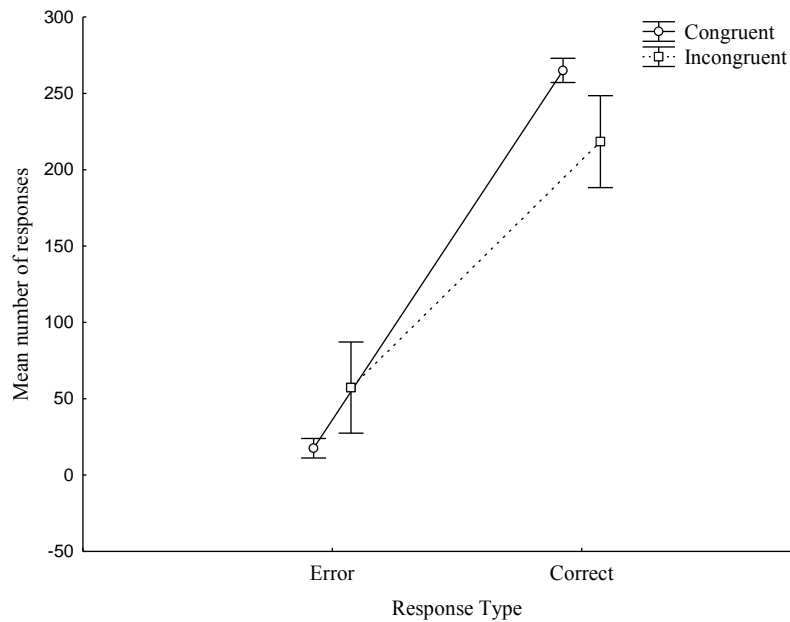
## Results

### Behavioural Analyses

The three-way ANOVA conducted on reaction time data indicated that mean reaction time on error trials ( $M = 516.20$  ms,  $SE = 24.39$  ms) was not significantly different from that on correct trials ( $M = 527.94$  ms,  $SE = 16.86$  ms),  $F(1, 17) = 0.48$ ,  $MSE = 5270$ ,  $p = .49$ ,  $\eta^2 = .03$ . No other main effects or interactions reached significance.

Error rates ranged from 2% to 44% across participants with a mean error rate of 13.2%. The three-way ANOVA conducted on accuracy data revealed a significant main effect of Response Type,  $F(1, 17) = 148.75$ ,  $MSE = 5196$ ,  $p < .001$ ,  $\eta^2 = .90$  and a significant main effect of Congruency,  $F(1, 17) = 5.57$ ,  $MSE = 40$ ,  $p = .03$ ,  $\eta^2 = .25$  which were modified by a significant Response Type  $\times$  Congruency interaction,  $F(1, 17) = 13.36$ ,  $MSE = 2583$ ,  $p = .001$ ,  $\eta^2 = .44$  (see Figure 15). As can be seen in Figure 12, and confirmed by Tukey post hoc tests, there were significantly more correct responses to congruent stimuli compared to errors to congruent and incongruent stimuli ( $ps < .001$ ), and significantly more correct responses to incongruent stimuli than errors to both congruent and incongruent stimuli ( $ps < .001$ ). While no further comparison reached significance ( $ps > .05$ ), Figure 12 indicates that there were more correct responses to congruent stimuli than to incongruent stimuli,

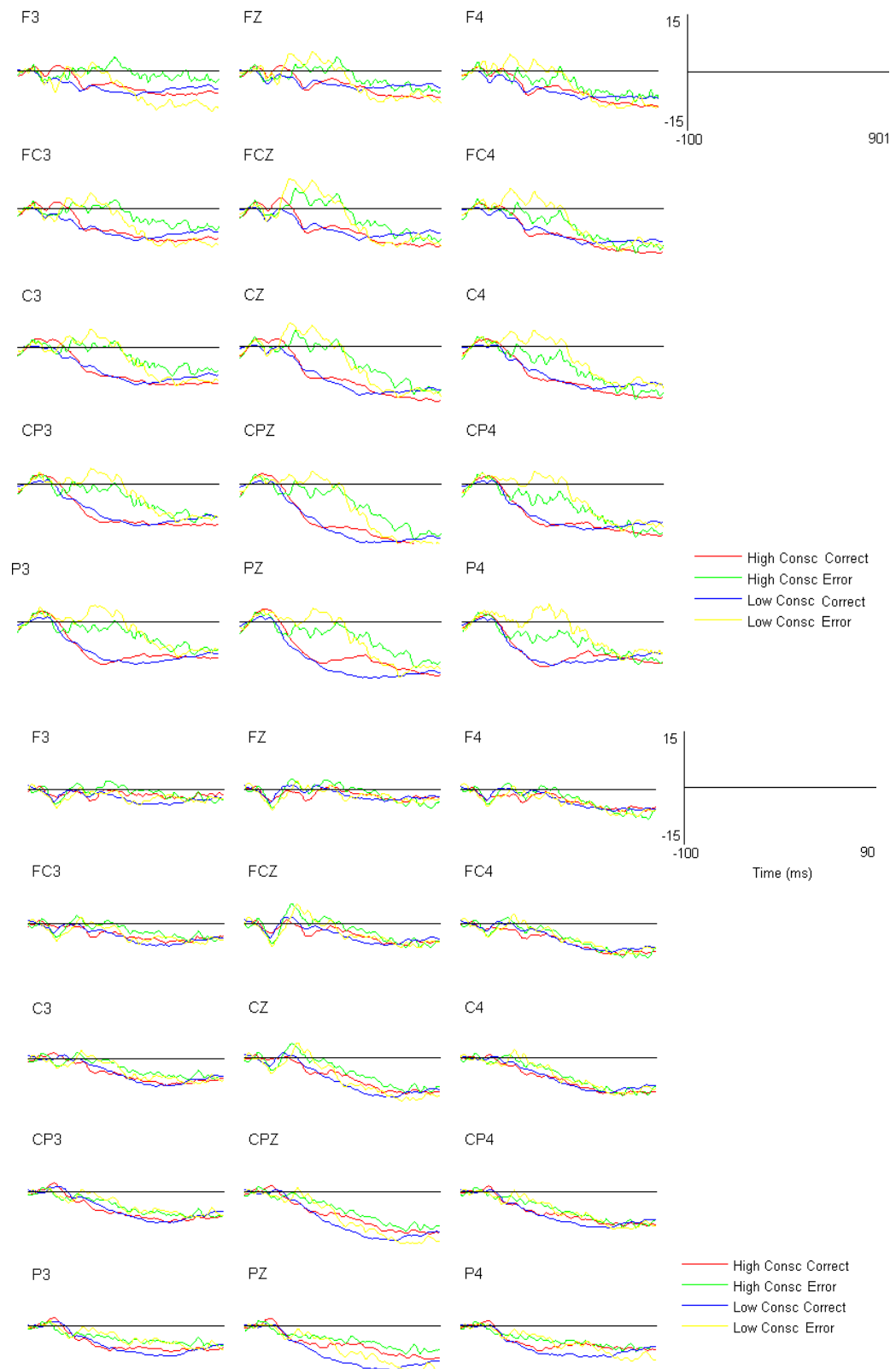
but more errors to incongruent compared to errors to congruent stimuli. No significant main effects or interactions involving levels of conscientiousness reached significance.



*Figure 12.* Mean number of error and correct responses to congruent and incongruent stimuli (vertical bars denote 95% confidence intervals).

### **Grand Mean Averages**

Perusal of grand mean averages confirmed that ERN/Ne and CRN was maximal at frontal, and fronto-central midline sites (see Figure 13). This is similar to the findings of other researchers (e.g., Falkenstein et al., 1991; Falkenstein et al., 2000; Gehring et al., 1993; Hajcak et al., 2004; Yeung et al., 2004) and the findings of Experiment 1. Choice of epoch from which mean amplitude for the ERN/Ne and CRN component was measured was 0 – 100 ms post response.



*Figure 13.* Grand mean averages for correct and error responses for high and low conscientious participants in congruent (top panel) and incongruent (bottom panel) conditions.

Early positive activity was also noted frontally, again with correct and error response-related activity showing clear amplitude differences. An early positive peak occurring approximately 120 ms post correct responses and a further peak at approximately 200 ms was associated with error responses. Since these peaks displayed a longer latency than those elicited during the two-choice flanker task (Experiment 1) the choice of measurement window for the early correct response-related positivity, and the early error response-related positivity was different, 50 – 200 ms and 120 – 300 ms, respectively. The correct response-related positivity displayed a clear reduction in amplitude compared to the error response-related positivity.

Perusal of the grand mean averages revealed a slow going wave that increased in negativity as the activity became more parietal in presentation, with error related activity appearing to be more positive in amplitude than correct related activity. As with Experiment 1, the epoch chosen to measure this activity was 300 – 600 ms post response.

In both congruent and incongruent conditions an early negative deflection is apparent at frontal and fronto-central sites. In the congruent condition (Figure 13, top panel) there appears to be a marked difference between error and correct response-related activity in later slower going activity, with correct response activity being considerably more negative than error related activity. This is not the case in the incongruent condition (Figure 13, bottom panel) with little difference apparent in activity across most sites. However, at Pz in the incongruent condition, error and correct response activity associated with high conscientiousness appears more positive than error and correct response-related activity associated with low conscientiousness.

## Electrophysiological Analyses

A comparison of mean amplitude was completed for ERN/Ne and CRN, early Pe and Pc, and late Pe and Pc, in order to determine whether overall error and correct response-related activity were significantly different. In each case error response-related activity was significantly larger than correct response-related activity ( $ps < .05$ ).

The four-way ANOVA conducted on ERN/Ne and CRN mean amplitude data showed a significant main effect of Response Type,  $F(1, 17) = 7.02$ ,  $MSE = 11.11$ ,  $p = .02$ ,  $\eta^2 = .29$  which was modified by a Response Type  $\times$  Sagittal Site interaction,  $F(1, 17) = 5.18$ ,  $MSE = 0.47$ ,  $p = .04$ ,  $\eta^2 = .24$  (see Figure 14). Tukey post hoc tests confirmed that while there were no significant differences in mean amplitude across sagittal sites for error responses ( $ps > .05$ ), error responses elicited significantly larger negativity than correct responses at both Fz ( $p < .001$ ) and FCz ( $p < .001$ ), and this difference was larger at FCz than at Fz.

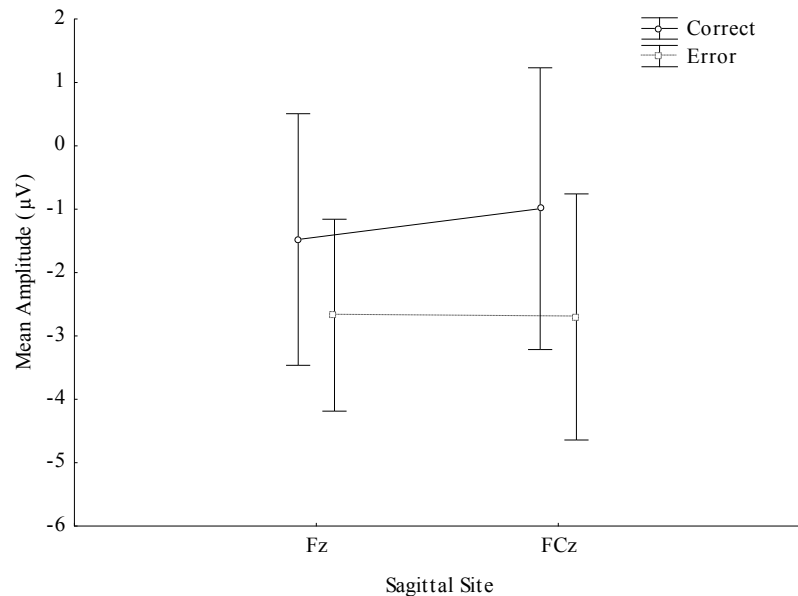


Figure 14. ERN/Ne and CRN mean amplitude for correct and error responses at Fz and FCz (vertical bars denote 0.95 confidence intervals).



The four-way ANOVA conducted on early Pe and Pc mean amplitude data also revealed a significant main effect of Response Type,  $F(1, 17) = 10.96$ ,  $MSE = 19.68$ ,  $p < .004$ ,  $\eta^2 = .39$  which was modified by a Response Type  $\times$  Sagittal Site interaction,  $F(1, 17) = 20.89$ ,  $MSE = 1.42$ ,  $p < .001$ ,  $\eta^2 = .55$  (see Figure 15). Tukey post hoc tests indicated that there was no significant difference in mean amplitude across Fz and FCz for correct responses ( $p < .05$ ), however error responses elicited significantly larger positive activity at both Fz and FCz than correct responses ( $ps < .001$ ) and error response activity showed a significantly larger positivity at FCz compared to Fz ( $p < .001$ ).

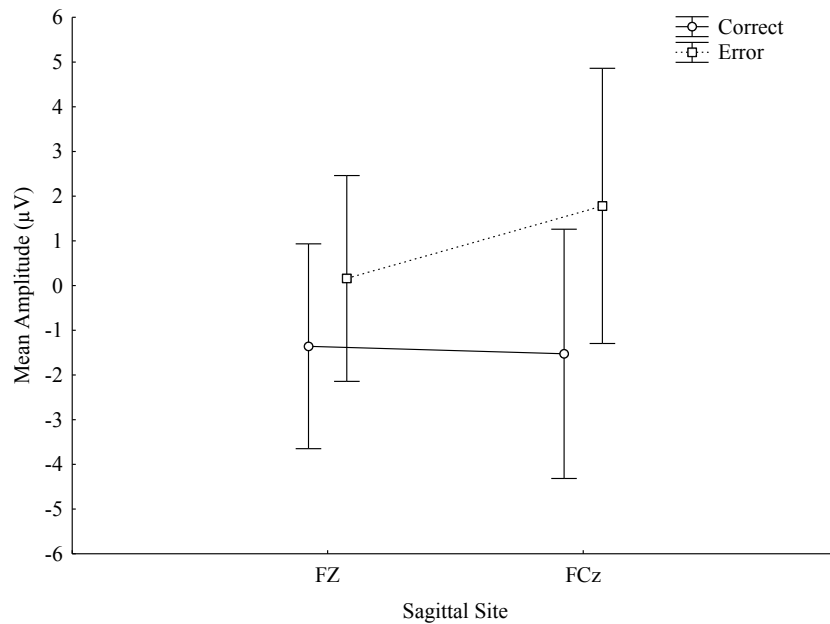
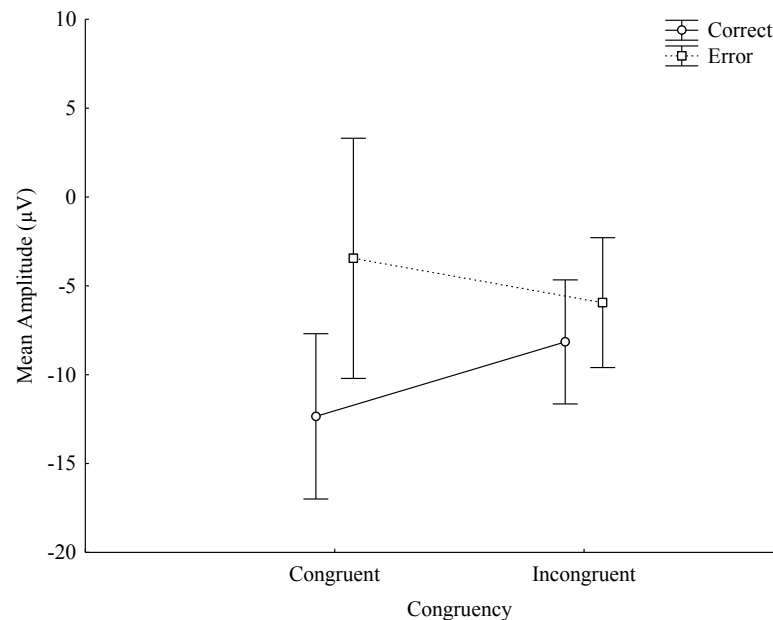


Figure 15. Early Pe and Pc mean amplitude for correct and error responses at Fz and FCz (vertical bars denote 0.95 confidence intervals).

The four-way ANOVA conducted on late Pe and Pc amplitude data revealed a significant main effect of Response Type,  $F(1, 17) = 34.61$ ,  $MSE = 33.03$ ,  $p < .001$ ,  $\eta^2 = .67$ , which was modified by a significant Response Type  $\times$  Congruency interaction,  $F(1, 17) = 9.41$ ,  $MSE = 43.97$ ,  $p = .007$ ,  $\eta^2 = .36$  (see Figure 16). Tukey post hoc tests indicated that mean amplitude was significantly more positive for error

responses in the congruent condition compared to correct responses in the congruent and incongruent conditions ( $ps < .01$ ). Error responses also elicited significantly larger mean positivity in the incongruent condition compared to correct responses in the congruent condition ( $p < .05$ ) but were not significantly different to correct responses to congruent stimuli ( $p > .05$ ). This four-way analysis also showed that overall mean amplitude was significantly more positive at Pz ( $M = -6.86$ ,  $SE = 1.29$ ) than at FPz ( $M = -8.08$ ,  $SE = 1.44$ ),  $F(1, 17) = 5.03$ ,  $MSE = 11.09$ ,  $p = .04$ ,  $\eta p^2 = .23$ . No other main effects or interactions reached significance.



*Figure 16.* Late Pe and Pc mean amplitude to congruent and incongruent stimuli (vertical bars denote 0.95 confidence intervals).

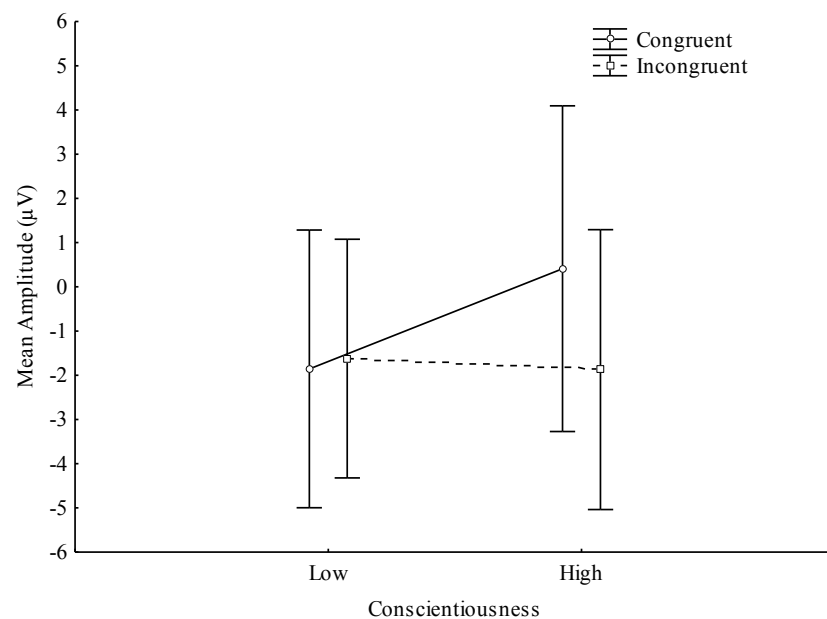
Separate analyses of each response related component (ERN/Ne, CRN and early and late Pe and Pc) were undertaken and are presented below.

### **ERN/Ne**

The three-way ANOVA conducted on ERN/Ne mean amplitude data showed no significant main effects or interactions.

## CRN

The three-way ANOVA conducted on CRN mean amplitude data revealed a significant Congruency  $\times$  Conscientiousness interaction,  $F(1, 17) = 4.56$ ,  $MSE = 6.44$ ,  $p < .048$ ,  $\eta^2 = .21$  (see Figure 17). Whereas post hoc tests indicated that no individual comparison reached significance ( $ps > .05$ ), Figure 17 shows that high conscientious participants produced larger negative mean amplitudes in the incongruent condition compared to the congruent condition while there was little difference according to congruency for low conscientious participants. Whereas, incongruent stimuli elicited similar CRN mean amplitude irrespective of conscientiousness, congruent stimuli elicited larger mean CRN amplitude for low compared to high conscientious participants. No further main effects or interactions reached significance.



*Figure 17.* CRN mean amplitude to congruent and incongruent stimuli for low and high conscientious groups (vertical bars denote 0.95 confidence intervals).

### Early Pe

The three-way ANOVA conducted on early Pe mean amplitude data revealed that overall mean amplitude was significantly more positive at FCz ( $M = 3.16$ ,  $SE = 1.38$ ) than at Fz ( $M = 1.08$ ,  $SE = 1.03$ ),  $F(1, 17) = 9.73$ ,  $MSE = 8.05$ ,  $p = .006$ ,  $\eta p^2 = .36$ . A trend approaching significance for a Congruency  $\times$  Sagittal Site interaction was also evident,  $F(1, 17) = 3.79$ ,  $MSE = 1.92$ ,  $p = .07$ ,  $\eta p^2 = .18$  (see Figure 18). As can be seen in Figure 18 and confirmed by Tukey post hoc tests, overall early Pe mean amplitude elicited by both congruent and incongruent stimuli was significantly more positive at FCz compared to Fz ( $ps < .001$ ) and congruent stimuli elicited larger mean positivity than incongruent stimuli at FCz ( $p < .05$ ) with no significant difference at Fz ( $p > .05$ )

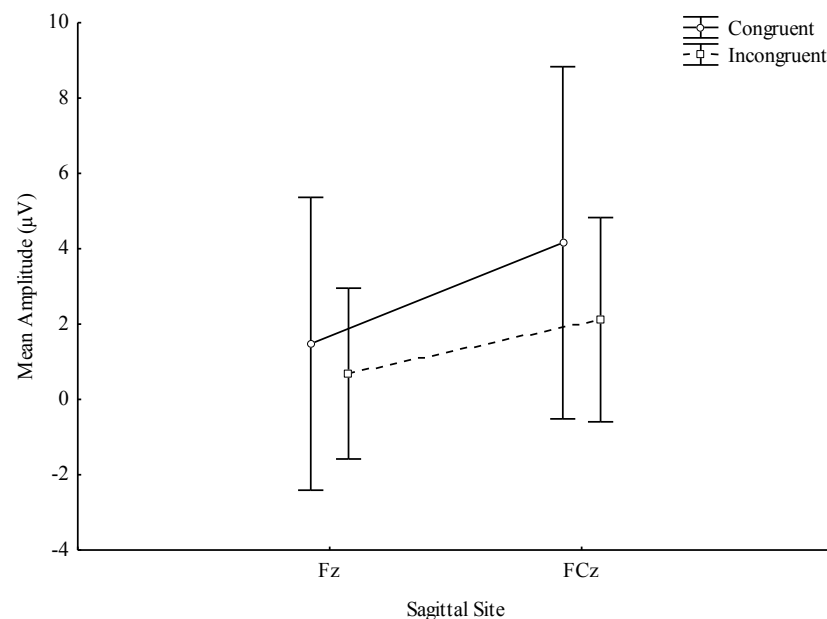
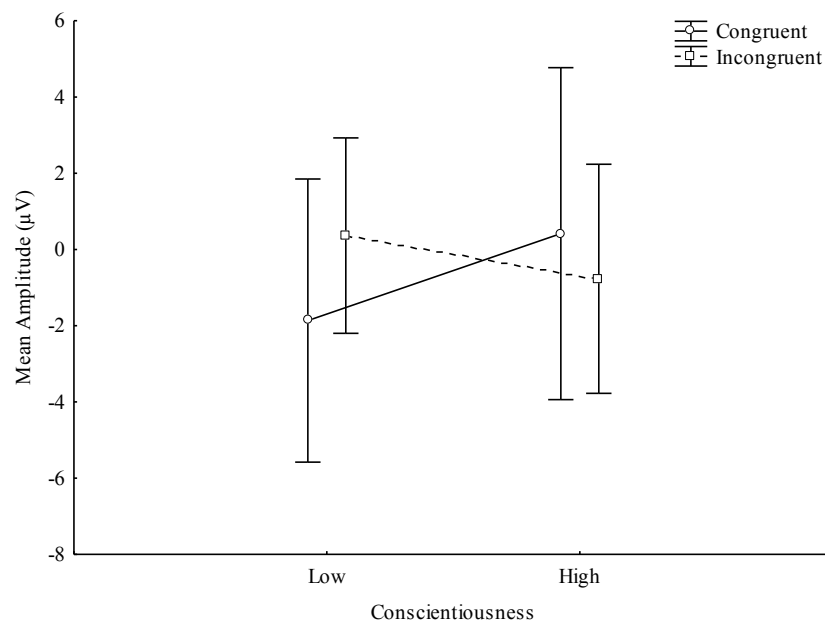


Figure 18. Early Pe mean amplitude to congruent and incongruent stimuli at Fz and FCz (vertical bars denote 0.95 confidence intervals).

### Early Pc

The three-way ANOVA conducted on early Pc mean amplitude data revealed a significant Congruency  $\times$  Conscientiousness interaction,  $F(1, 17) = 4.83$ ,  $MSE = 11.18$ ,  $p = .04$ ,  $\eta^2 = .22$  (see Figure 19). Tukey post hoc tests failed to reveal any statistically significant differences between individual means ( $ps > .05$ ), however Figure 19 shows that mean amplitude to incongruent stimuli was more positive for low conscientious than high conscientious participants and, in the congruent condition, high conscientious participants demonstrated more positive activity than low conscientious participants. Low conscientious participants demonstrated larger mean positivity in the incongruent condition than the congruent condition and conversely high conscientious participants displayed larger positivity in the congruent compared to the incongruent condition. No other main effects or interactions reached significance.



*Figure 19.* Early Pc mean amplitude to congruent and incongruent stimuli for low and high conscientious participants (vertical bars denote 0.95 confidence intervals).

### **Late Pe**

The three-way ANOVA conducted on late Pe mean amplitude data showed that mean amplitude tended to be more positive at Pz ( $M = -4.01$ ,  $SE = 1.50$ ) compared to CPz ( $M = -5.38$ ,  $SE = 1.64$ ),  $F(1, 17) = 4.06$ ,  $MSE = 8.54$ ,  $p = .06$ ,  $\eta^2 = .19$ . No other main effects or interactions reached significance.

### **Late Pc**

The three-way ANOVA conducted on late Pc mean amplitude data indicated that incongruent stimuli ( $M = -8.15$ ,  $SE = 1.17$ ) elicited significantly larger mean positive activity than congruent stimuli ( $M = -12.34$ ,  $SE = 1.56$ ),  $F(1, 17) = 20.20$ ,  $MSE = 16.11$ ,  $p < .001$ ,  $\eta^2 = .54$ . A trend approaching significance was also evident for a main effect of Sagittal Site,  $F(1, 17) = 4.07$ ,  $MSE = 5.35$ ,  $p = .06$ ,  $\eta^2 = .19$ . Mean amplitude tended to be more positive at Pz ( $M = -9.71$ ,  $SE = 1.22$ ) compared to CPz ( $M = -10.79$ ,  $SE = 1.42$ ).

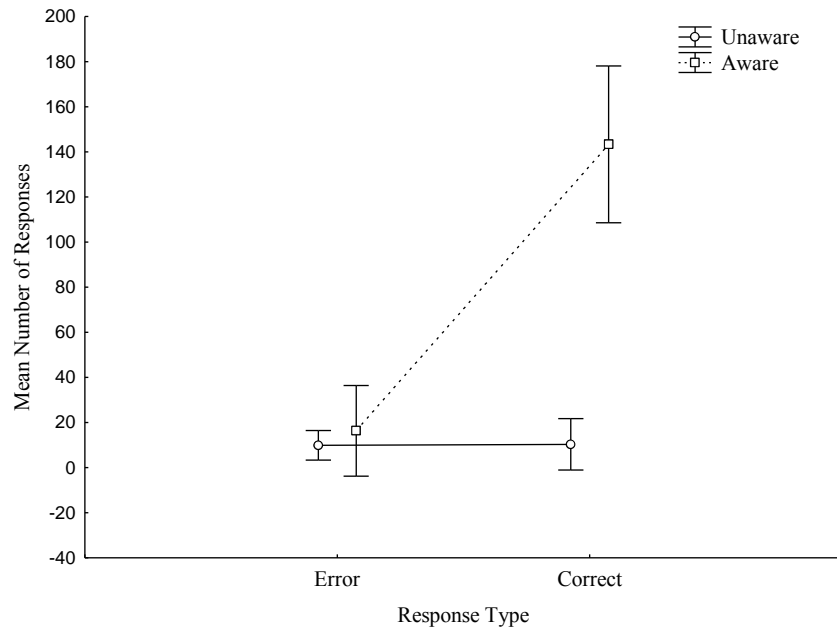
### **Response Awareness**

The analyses of data associated with response awareness are presented below. A separate analysis of data associated with incongruent stimuli only was conducted because there were insufficient responses where participants were unaware of their responses to congruent stimuli. The examination of the impact of conscientiousness within this analysis was also not possible because there were not enough high conscientious participants to create high and low conscientious groups within this sample.

### Behavioural analyses

The two-way ANOVA conducted on reaction time data within aware and unaware conditions showed that overall, reaction time to errors ( $M = 629.72$ ,  $SE = 86.31$ ) was not significantly different to correct responses ( $M = 771.90$ ,  $SE = 149.49$ ),  $F(1, 10) = 0.68$ ,  $MSE = 134094$ ,  $p = .43$ ,  $\eta^2 = .06$ . However, reaction time to stimuli when participants were aware of their response type was significantly faster ( $M = 582.78$ ,  $SE = 118.56$ ) than when participants were not aware of their response type ( $M = 818.84$ ,  $SE = 76.15$ ),  $F(1, 10) = 5.62$ ,  $MSE = 44617$ ,  $p = .04$ ,  $\eta^2 = .36$ . No other main effects or interactions reach significance.

The two-way ANOVA conducted on accuracy data revealed significant main effects of Response Type,  $F(1, 10) = 36.09$ ,  $MSE = 506.31$ ,  $p < .001$ ,  $\eta^2 = .78$  and Response Awareness,  $F(1, 10) = 72.31$ ,  $MSE = 302.51$ ,  $p < .001$ ,  $\eta^2 = .88$  which were modified by a significant Response Type  $\times$  Response Awareness interaction,  $F(1, 10) = 59.56$ ,  $MSE = 302.51$ ,  $p < .001$ ,  $\eta^2 = .86$  (see Figure 20). As can be seen in Figure 20, and confirmed by Tukey post hoc tests, there were significantly more aware correct responses than unaware correct and error responses ( $ps < .001$ ) and significantly more aware correct responses than aware error responses ( $p < .001$ ). There were no significant differences in the number of aware and unaware error responses and also no significant differences in the number of aware error and correct responses ( $ps > .05$ ).



*Figure 20.* Mean number of aware and unaware error and correct responses (vertical bars denote 0.95 confidence intervals).

### **Grand mean averages**

Grand mean average waveforms were obtained for correct and incorrect responses in the incongruent condition only, and these were broken down by levels of participant awareness to their response (aware/unaware). Figure 21 shows, as with the overall grand means, a clear negative deflection occurring early post response (approximately 50 ms). This is followed by an early positive deflection that appears as a larger positive peak for correct responses where participants were aware with little difference in appearance for activity associated with other response types. A later slow going wave that, for the most part is negative, is also evident. This late activity follows a similar pattern to that of the earlier activity.



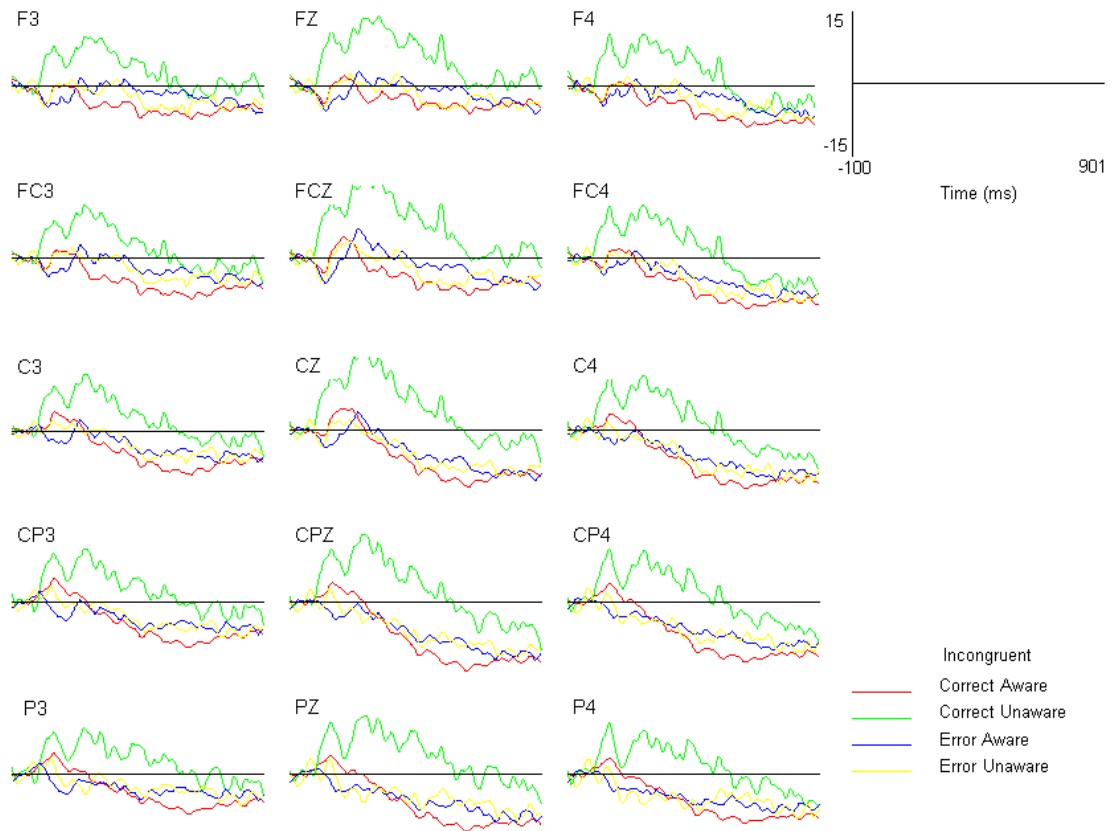


Figure 21. Grand mean average waveforms for error and correct responses to incongruent stimuli when participants were aware and unaware of their responses.

### Electrophysiological analyses

The three-way ANOVA conducted on ERN/Ne and CRN mean amplitude data revealed significant main effects of Response Type,  $F(1,10) = 7.77$ ,  $MSE = 41.69$ ,  $p = .02$ ,  $\eta^2 = .44$ , which was modified by a Response Awareness  $\times$  Response Type interaction trend,  $F(1, 10) = 4.30$ ,  $MSE = 27.52$ ,  $p = .06$ ,  $\eta^2 = .46$  (see Figure 22). Tukey post hoc tests revealed that when participants were aware of both error and correct responses, they demonstrated a significantly larger mean negativity than when they were not aware of correct responses only ( $ps < .05$ ). While no other

comparisons reached significance ( $ps > .05$ ), Figure 22 indicates that ERN/Ne and CRN mean amplitude are more differentiated in the unaware condition compared to the aware condition where there is little mean amplitude difference. Overall, mean amplitude tended to be more negative at Fz ( $M = 0.21$ ,  $SE = 1.16$ ) than at FCz ( $M = .92$ ,  $SE = 1.00$ ),  $F(1, 10) = 4.53$ ,  $MSE = 1.01$ ,  $p = .06$ ,  $\eta p^2 = .31$ . No other main effects or interactions reach significance.

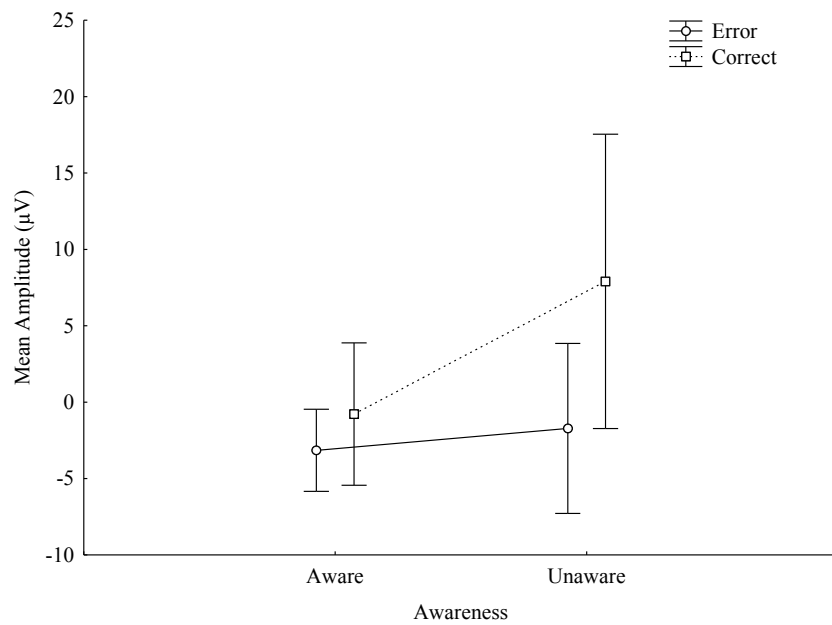
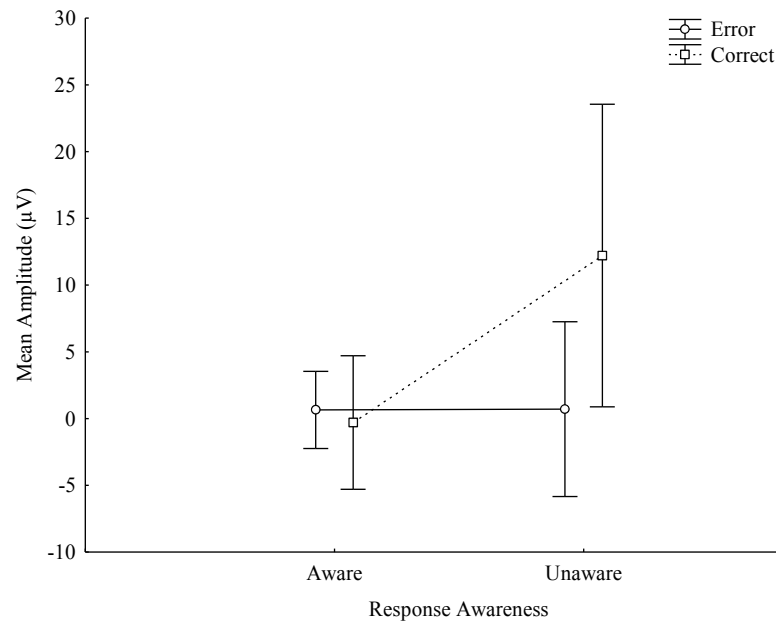


Figure 22. ERN/Ne and CRN mean amplitude in aware and unaware conditions (vertical bars denote 0.95 confidence intervals).

The three-way ANOVA conducted on early Pe and Pc mean amplitude data revealed significant main effects of Response Type,  $F(1, 10) = 6.32$ ,  $MSE = 39.72$ ,  $p = .03$ ,  $\eta p^2 = .39$ , which was modified by a significant Response Type  $\times$  Response Awareness interaction,  $F(1, 10) = 6.56$ ,  $MSE = 53.11$ ,  $p = .03$ ,  $\eta p^2 = .40$  (see Figure 23).



*Figure 23.* Early Pe and Pc mean amplitudes in aware and unaware conditions (vertical bars denote 0.95 confidence intervals).

Tukey post hoc tests confirmed that when participants were aware of their responses, irrespective of whether they were erroneous or correct, they showed a significantly less positivity than when participants were not aware of correct responses only ( $ps < .01$ ). While no other comparisons reached significance ( $ps > .05$ ), Figure 23 indicates that early Pe and Pc mean amplitude were more differentiated in the unaware condition compared to the aware condition where there is little mean amplitude difference. No other main effects or interactions reached significance.

The three-way ANOVA conducted on late Pe and Pc mean amplitude data showed no significant main effects or interactions involving Response Type ( $ps > .05$ ). No other main effects or interactions reached significance.

Separate analyses of error and correct response-related components revealed no significant main effects or interactions ( $ps > .05$ ).

## Discussion

As predicted, overall error responses produced significantly larger mean amplitudes than correct responses across early and late components. Contrary to the expected outcome, the impact of task difficulty and conscientiousness was not evident in error-related components; the influence of these factors was only seen in correct response-related activity. Conscientiousness was found to moderate congruency effects for correct responses within early time windows, again not supporting hypothesised outcomes. No evidence was found to support the explanation of Pe as a reflection of conscious error awareness.

ERN/Ne and CRN mean amplitude differences evidenced in this experiment are consistent with the outcomes of Experiment 1 and again explainable within the theoretical framework put forward by Falkenstein et al. (1990, 1991) in which it is argued that the negative deflections represent a comparative process that involves the monitoring and evaluation of correct and error responses.

Whereas behavioural data suggests that the incongruent flanker condition was more difficult than the congruent condition, with reaction times significantly faster to congruent stimuli than incongruent stimuli, this difference was not reflected in differences in the mean amplitudes of the error response-related components (ERN/Ne, early Pe and late Pe). Congruency effects moderated by conscientiousness levels were apparent in CRN mean amplitudes. Specifically, low conscientious participants showed no significant difference in CRN mean amplitude according to congruency levels, whereas high conscientious participants tended to elicit larger negativity to incongruent stimuli compared to congruent stimuli. Interestingly, this effect was in the opposite direction to that found for ERN/Ne in the less demanding, two-choice flanker task used in Experiment 1 and points to an explanation involving

the increasing task difficulty in Experiment 2. With this in mind, errors may be less recognisable and therefore less salient in the more demanding four-choice, compared to the two-choice, flanker task and as such the focus of the early evaluative processes is redirected to correct responses. This then provides an explanation of the lack of conscientiousness effects in terms of error responses in the four-choice flanker task. Accordingly, conscientiousness can then be applied to an explanation of the differences in CRN amplitudes. Perhaps those with high levels of conscientiousness, who are more actively engaged in task related behaviours (Ashton & Lee, 2001), invest effort in completing tasks and evaluating responses according to task demands and this is reflected in differing CRN mean amplitudes. If this is the case then motivational significance is not confined specifically to error responses, as was argued by Hajcak et al. (2005), but rather is applied to responses according to task demands. Again, effects of conscientiousness evident in early Pc suggest the salience of responses may extend beyond early negativities as was originally shown (Hajcak et al., 2005; Pailing & Segalowitz, 2004a).

Congruency effects alone were evident in the late Pc, with incongruent stimuli eliciting a larger positivity than congruent stimuli. While these congruency effects are difficult to reconcile within current theories of response evaluation and monitoring (Falkenstein, 1990; Holroyd & Coles, 2002; Yeung et al., 2004), they nonetheless indicate that the time course of response evaluation processes extends beyond early components and demonstrates a functional separation of error and correct related components at this later time point. Response-related components occurring within late time-windows have received little attention in the literature; however researchers have put forward explanations in terms of the effects of conscious recognition and monitoring of responses (Burgio-Murphy et al., 2007;

Endrass et al., 2007). Congruency effects in the late time-window may thus be an indicator of conscious response evaluation with amplitude differences reflecting the impact of the effort required to consciously evaluate responses according to task demands. Why this effect was not evident for error responses is not clear; however this maybe due to differences in conscious awareness of response types although this could not be confirmed within the current experiment due to data limitations.

The investigation of awareness of responses was a key aim of this series of experiments. Response certainty as described by previous researchers (Scheffers & Coles, 2000; Pailing & Segalowitz, 2004b), was more clearly explicated within this experimental paradigm which allowed for direct questioning regarding awareness of responses. However, as was the case with Experiment 1, analysis of data in terms of response awareness was confined to that associated with incongruent stimuli only, due to insufficient numbers of responses where participants were unaware of response types to congruent stimuli. Overall analyses showed response awareness effects in early negative and positive response-related components. In each instance, mean amplitudes in unaware conditions were significantly larger than those for aware conditions, and were moderated by response type in both the ERN/Ne and CRN and early Pe and Pc comparisons with only CRN and early Pc showing differentiation in terms of levels of awareness. Separate analyses of all components failed to reveal any significant differences in terms of awareness of responses.

These findings are not consistent with predictions concerning the response awareness hypothesis of Pe and past research findings indicating activity to be more pronounced at Pe for aware conditions compared to unaware conditions (Scheffers & Coles, 2000; Endrass et al., 2005; Nieuwenhuis et al., 2001). Whereas these outcomes suggest that awareness of responses may play a role in the modulation of activity

associated with response evaluation, this role extends beyond error responses, as originally thought (Endrass et al., 2005; Nieuwenhuis et al., 2001), to correct response-related activity. Such claims, however, are made with caution since small sample sizes preclude decisive inferences being made.

On the whole, Experiment 2 has provided further support for the argument that task demands and individual differences play a role in modulating response-related ERP components. The effects of conscientiousness were moderated by task demands in the four-choice flanker, but found to impact early correct related activity compared to error responses in the two-choice flanker (Experiment 1). This suggests that with an increase in overall task difficulty, correct responses may become more salient than errors. In addition, these findings provide a foundation on which further investigation of the impact of task and response salience, task difficulty, and conscientiousness in terms of both correct and error response-related activity is warranted. Considering these outcomes, Experiment 3 was designed to examine the impact of task demands, task salience and conscientiousness in a language based task. Measures of response awareness were also included in this experiment in an effort to clarify the impact of response awareness on response-related processes.

## **Chapter 7**

### **Experiment 3:**

#### **Task Salience, Conscientiousness and Response Awareness -**

##### **Modulators of Response-related ERP Components**

In order to investigate the effects of task and response salience, the final experiment in this series was broadly based on the research completed by Pailing and Segalowitz (2004a) and Hajcak et al. (2005). In an effort to influence task and response salience these researchers manipulated the value of responses by assigning a point or monetary value to each trial. Pailing and Segalowitz (2004a) applied a small monetary incentive (0, 0.25 or 0.75 cents per correct response) differentially across four motivational conditions and two response types with participants able to earn a maximum of \$5.00 per condition. The researchers point out, however, that only 39% of participants indicated that they considered the motivation manipulation to be effective. Hajcak et al. (2005) manipulated the value of responses by associating a point value to each trial (5 = low, 100 = high) that was to be converted to a monetary value at the end of the experiment, with bonuses based on performance. However, performance was unrelated to reward with all participants receiving \$5.00 for their participation. The current experiment followed a less complex incentive manipulation, similar to Hajcak et al. (2005), with the addition of a nil incentive level (0 points) to allow a more precise investigation of the effect of the subjective importance of tasks and associated responses. A monetary prize of \$50.00 was awarded to the participant with the highest accrued point value. Offering one single substantial monetary prize was intended to maximise motivation and, in turn, the salience of tasks and responses associated with high point level trials.

Hajcak et al. (2005) noted that activity following the ERN/Ne showed a



sustained negativity when motivation was manipulated via monetary incentive. However, in a follow-up study where motivation was controlled via performance evaluation the researchers observed larger positive activity following the ERN/Ne. While this difference was not formally analysed, it suggests that response-related components other than ERN/Ne may also be impacted by levels of task or error salience and provided a rationale to explore this further. In addition, conscientiousness effects evident in early Pe amplitude differences in the less demanding two-choice flanker task (Experiment 1), compared to conscientiousness effects found in CRN and early Pc in the more demanding four-choice flanker task (Experiment 2), further suggest that the effects of task or response salience extend beyond the ERN/Ne to later and correct response-related components. Thus the inclusion of measures of conscientiousness together with the application of monetary incentives linked to correct responses was intended to allow for a more precise measure of individual differences in task and response salience and their influence on early and late response-related components (Pailing & Segalowitz, 2004a).

Overall mean amplitude elicited by error responses was expected to be larger than that elicited by correct responses. It was expected that, in accordance with the findings of Hajcak et al. (2005), ERN/Ne amplitude would increase relative to incentive manipulations. If the early or late Pe or Pc components are also associated with the salience of errors then the amplitude of these components would also increase relative to these manipulations. It was further hypothesised that the level of sensitivity to incentive manipulations would be moderated by conscientiousness, such that those who scored high on conscientiousness measures would display similar ERN/Ne amplitudes irrespective of these incentive manipulations whereas those who score low on a conscientiousness measure would be sensitive to incentive

manipulations and ERN/Ne amplitudes would increase accordingly. Again, if task salience is a factor that impacts later response-related components, then early and late Pe amplitudes will follow similar patterns to ERN/Ne.

The use of language based tasks in the investigation of response-related processes is relatively recent, with researchers focusing on error processing in terms of reading disorders or word recognition (Horowitz-Kraus & Breznitz, 2008; Sebastian-Gallés et al., 2006). These tasks also provide an opportunity to explore the impact of task demands with task difficulty defined as greater in phonological than orthographic decision tasks. Increased reaction time and error rates in phonological compared to orthographic tasks support this claim (e.g., Kramer & Donchin, 1987). Since Experiments 1 and 2 demonstrated that task demands are reflected in ERP correlates of response monitoring and are modulated by the influence of conscientiousness levels, this task also provided the opportunity to further explore the interplay of task demands and individual differences within a language based task. In accordance with the outcomes of Experiments 1 and 2 it was generally expected that correct responses to the less demanding orthographic task would reflect lower mean amplitudes than correct responses to the more difficult phonological decision task, which would in turn be moderated by levels of conscientiousness.

Since questions remain regarding the role of response awareness following Experiments 1 and 2, measurement of this variable was again included to specifically investigate the error awareness hypothesis of Pe (Endrass et al., 2005; Endrass et al., 2007; Nieuwenhuis et al., 2001) and also to determine whether awareness of responses is evidenced in other response-related ERP components. If Pe is an index of error awareness then, in accordance with past research, Pe mean amplitude was expected to be larger for aware than unaware erroneous responses.

Ability to decode words and nonwords was fundamental to the completion of the experimental task so this was added as an independent variable to all analyses. Given that decoding ability had not yet been explored in the literature in terms of response-monitoring processes and associated components, hypotheses were tentative. Since it has been noted that good and poor phonological decoders display differing hemispheric activity when stimulus-locked activity is considered, some differentiation of response-related effects may be evidenced in hemispheric activity (Martin, Kaine, & Kirby, 2006).

## **Method**

### **Participants**

Sixty-one female, right-handed participants aged between 18 and 35 years (mean age = 20.56) were recruited from first year psychology students at the University of Tasmania and given course credit for their participation time. Participants were screened in the same manner as Experiments 1 and 2. Since this experiment used a task that required participants to decode nonwords, they were grouped according to a median split of their decoding ability scores on the Martin and Pratt Nonword Reading Test (Martin & Pratt, 2001). Those participants with a raw score of 45 or below were considered poor decoders and those with a raw score of 46 or above were considered good decoders. Participants were also grouped in relation to their levels of conscientiousness as measured by the NEO PI-R (Costa & McCrae, 1992), as per Experiments 1 and 2. Data from 24 participants were excluded because an insufficient number of error responses were made, leaving 37 participants with a mean age of 19.84 years whose data were included in analyses. Final group numbers were; high conscientious, good decoders, ( $n = 5$ ), low conscientious, good decoders,

( $n = 13$ ), high conscientious, poor decoders, ( $n = 12$ ) and low conscientious, poor decoders ( $n = 7$ ).

### **Apparatus**

The tasks were completed using Neuroscan Stim 3.1 software on a PC.

Electroencephalographic (EEG) data were recorded using Neuroscan SCAN 4.3.1 software on a PC and a 32 channel Quickcap with Ag/AgCl electrodes. Data acquisition procedures were the same as those described in Experiments 1 and 2.

### **Stimuli**

Participants completed two tasks: an orthographic and a phonological decision task. Each task consisted of five blocks of 60 trials of paired letter strings presented in 40 pt Times New Roman, white font on a black background. The stimuli were presented, in pairs, on a computer screen for 1000 ms and they appeared randomly, left and right of centre with the word midpoint 3.5 cm from fixation. A fixation point was presented prior to the onset of each stimulus pair. The orthographic decision task comprised six-letter words paired with six-letter pseudohomophones (e.g., plarck, plaque). A full list is presented in Appendix C. Words used for this task occurred within a written frequency range of 1 to 100 per 100,000 (Kucera & Francis, 1967). The phonological decision task comprised six-letter pseudohomophones paired with six-letter pronounceable non-words (e.g., whurce – whurne). A full list is presented in Appendix D. Each trial was preceded by a numerical cue (0, 20, and 100), indicating a points value associated with the following trial. This was presented in the centre of the screen for 2000 ms in 40 pt Times New Roman font. A response certainty screen followed each trial response with the question “Did you make an error?” appearing in the centre of the screen. The participant had four response options: no - very sure; no - somewhat sure; yes - somewhat sure; yes - very sure.

## **Procedure**

Completion of initial screening and set-up followed the same procedure as that in Experiments 1 and 2 except participants also completed the Martin and Pratt Nonword Reading Test (Martin & Pratt, 2001). Participants attended the Cognitive Psychophysiology Laboratory for a session totalling approximately three hours. Each counterbalanced task was explained and opportunity for practice given before presentation. The cued point value (0, 20, and 100) for each trial was explained, along with disclosing information that a prize of \$50 would be awarded to the participant who accrued the highest points score. The orthographic decision task required the participant to decide which word in the presented pair was a real word and respond appropriately by button press (left or right). The process was similar for the phonological decision task except participants were required to decide which word of the presented pair sounded like a real word. After completing each trial participants were asked to indicate whether their response was incorrect and how certain of this they were by appropriate button press. Participants were instructed to respond as quickly and accurately as possible. Rest periods followed each block of trials to prevent fatigue.

## **Design**

This experiment followed a 2 [Decoding Ability: poor, good]  $\times$  2 [Conscientiousness: high, low]  $\times$  2 (Task Type: orthographic, phonological)  $\times$  3 (Task Salience: low, moderate, high)  $\times$  2 (Response Awareness: aware, unaware)  $\times$  2 (Response Type: error, correct)  $\times$  5 (Sagittal Site: Fz, FCz, Cz, CPz, Pz)  $\times$  2 (Coronal Area: left, right) mixed design. The ERP dependent measures were ERN/Ne, CRN, early and late Pe and Pc mean amplitude and the behavioural

dependent measures were reaction time and accuracy of responses to orthographic and phonological decision tasks.

## **Analyses**

The analysis was limited to data associated with the phonological decision task because there were inadequate numbers of error responses to the orthographic decision task to enable inclusion of this response-related data. Analysis of ERN/Ne, CRN, early Pe and Pc data was confined to frontal and fronto-central sagittal regions as these components have been found to be maximal at these sites. Analysis of the late Pe and Pc was confined to centro-parietal and parietal regions since they have been found to be maximal in these regions (Endrass, 2005, 2007; Falkenstein et al., 1991, 2000; Gehring et al., 1993; Overbeek et al., 2005; Shalgi et al., 2009).

A series of three-, four- and five-way mixed measures ANOVAs were used to examine behavioural data and ERN/Ne, CRN, Pe and Pc mean amplitude. Reaction time and accuracy were analysed using a 2 [Decoding Ability: poor, good]  $\times$  2 [Conscientiousness: high, low]  $\times$  2 (Response Type: error, correct)  $\times$  3 (Task Salience: low, moderate, high) mixed measures ANOVA. Overall differences between error and correct response-related mean amplitudes were determined using a 2 [Decoding Ability: poor, good]  $\times$  2 [Conscientiousness: high, low]  $\times$  2 (Response Type: error, correct)  $\times$  3 (Task Salience: low, moderate, high)  $\times$  2 (Sagittal Site: Fz, FCz or CPz, Pz) mixed measures ANOVA. As was the case for Experiments 1 and 2, subsequent analyses were then conducted separately for error and correct response-related activity. In each case the sagittal variables were selected to reflect differing topography associated with early or late response-related activity. Data for the late positive response-related mean amplitude component was also analysed, in terms of averaged frontal coronal sites (left: F7 and F3; right: F8 and F4). A 2 [Decoding

Ability: poor, good]  $\times$  2 [Conscientiousness: high, low]  $\times$  2 (Response Type: correct, error)  $\times$  3 (Task Salience: low, moderate, high)  $\times$  2 (Coronal Area: left, right) five-way mixed measures ANOVA was conducted to examine hemispheric differences.

A further 2 [Decoding Ability: poor, good]  $\times$  2 (Response Awareness: aware, unaware)  $\times$  3 (Task Salience: low, moderate, high)  $\times$  2 (Sagittal Site: Fz, FCz or CPz, Pz) four-way mixed measures ANOVA was conducted to analyse the impact of response awareness on response-related components. Behavioural data associated with awareness of responses was analysed using a 2 [Decoding Ability: poor, good]  $\times$  2 (Response Awareness: aware, unaware)  $\times$  3 (Task Salience: low, moderate, high) mixed measures ANOVA. These analyses were confined to error-related activity due to computer programming constraints and did not include a Conscientiousness variable because high conscientious group numbers were too small ( $n=1$  and  $2$ ) to viably analyse. Group numbers in terms of decoding ability were: poor decoders ( $n=6$ ), and good decoders ( $n=5$ ).

All significance levels were maintained at  $p < .05$ , following Huynh-Feldt corrections where necessary. Significant main effects and interactions were followed up with breakdown ANOVAs and Tukey HSD post hoc tests where appropriate. Data from participants were included for analysis providing 20 or more correct and error responses were made in each experimental condition.

## **Results**

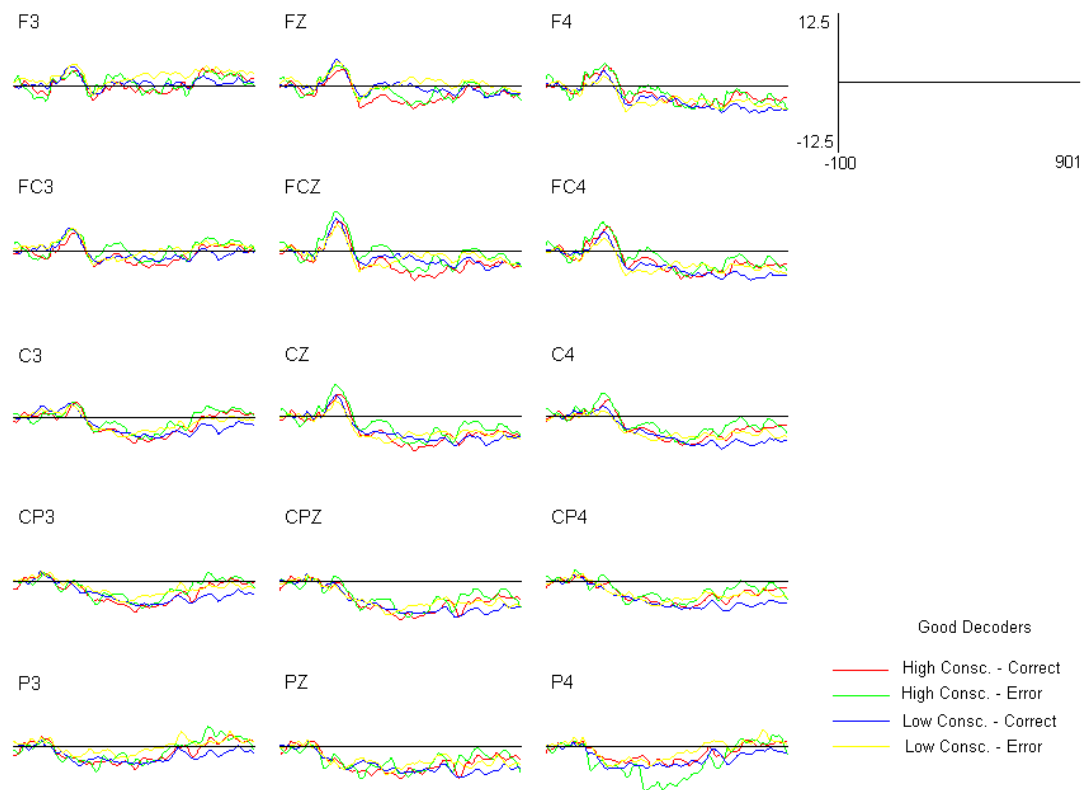
### **Behavioural Analyses**

The four-way ANOVA conducted on reaction time data for the phonological decision task indicated that reaction time to correct responses ( $M = 1.31$ ,  $SE = 0.09$ ) was significantly faster than to error responses ( $M = 1.39$ ,  $SE = 0.10$ ),  $F(1, 33) = 14.39$ ,  $MSE = 0.02$ ,  $p < .001$ ,  $\eta p^2 = .30$ . Error rates ranged from 19% to 49.66%

across participants with a mean error rate of 33.99%. The four-way ANOVA completed on accuracy data showed that participants produced significantly more correct responses ( $M = 63.74$ ,  $SE = 1.58$ ) than error responses ( $M = 33.52$ ,  $SD = 1.79$ ),  $F(1, 33) = -82.10$ ,  $MSE = 530.80$ ,  $p < .001$ ,  $\eta p^2 = .71$ . No other main effects or interactions for either reaction time or accuracy reached significance.

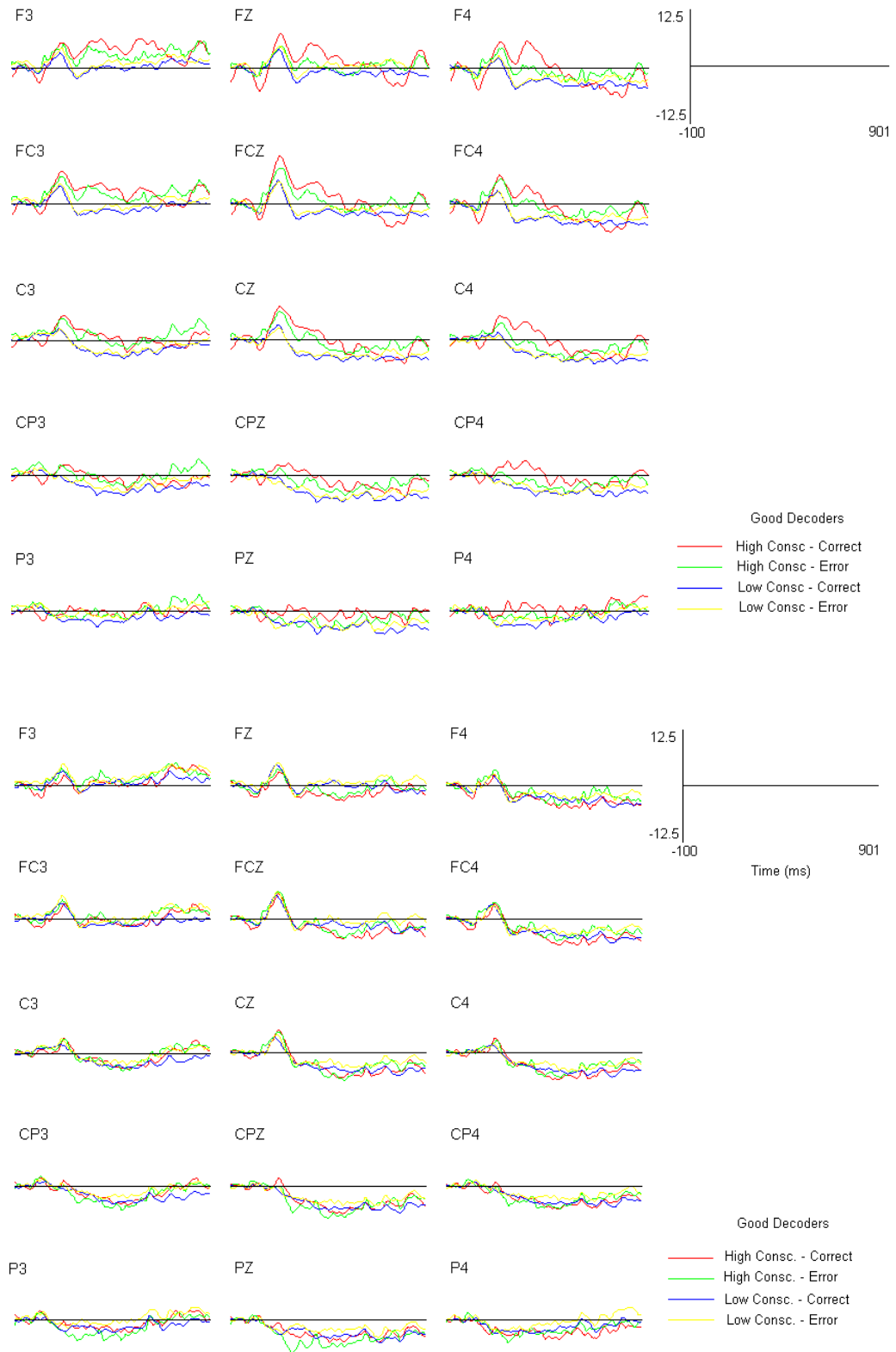
### Grand Mean Averages

Grand mean average waveforms were obtained for error and correct responses in the low, moderate and high task salience conditions for low and high conscientious, poor and good decoders (see Figures 24a, 24b, 24c, 24d).

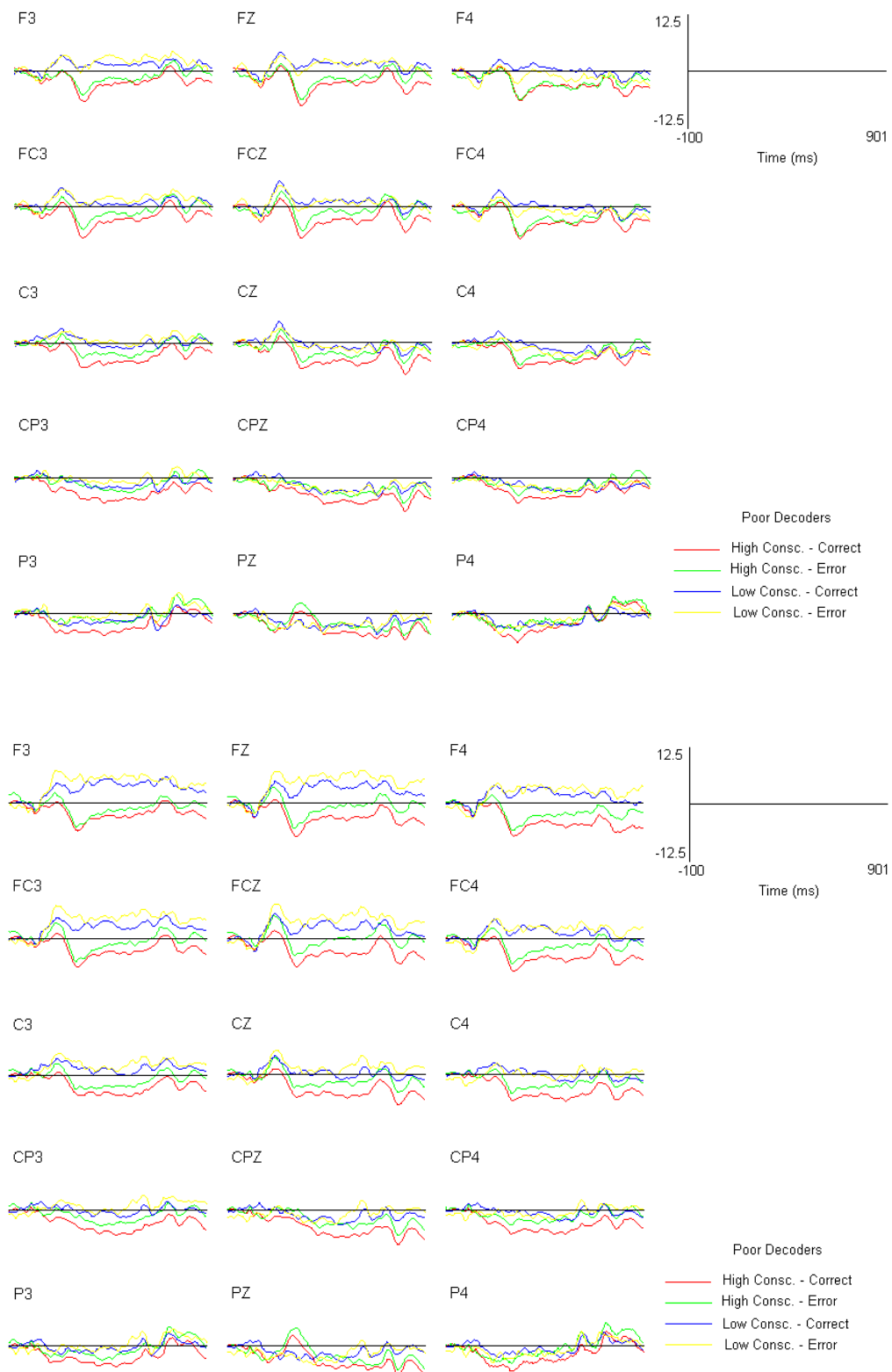


*Figure 24a.* Grand mean average waveforms for error and correct responses in the low task salience condition for high and low conscientious good decoders.

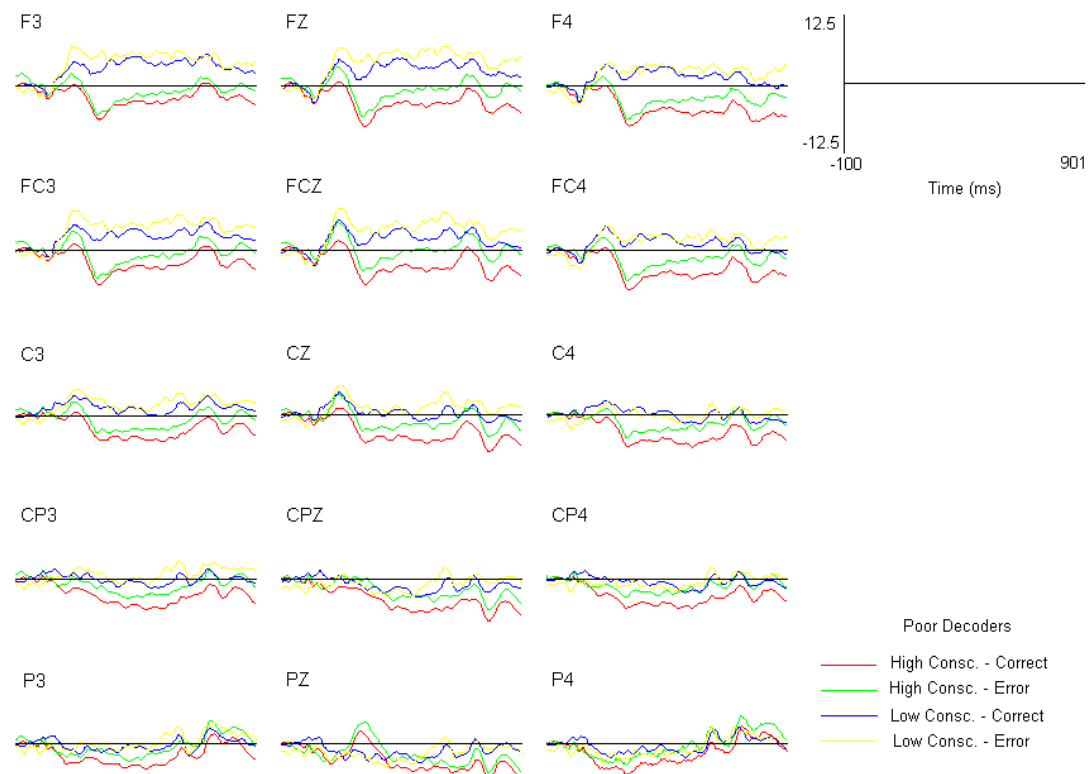




*Figure 24b.* Grand mean average waveforms for error and correct responses across moderate (top panel) and high (bottom panel) task salience conditions for high and low conscientious good decoders.



*Figure 24c.* Grand mean average waveforms for error and correct responses across low (top panel) and moderate (bottom panel) task salience conditions for high and low conscientious poor decoders.



*Figure 24d.* Grand mean average waveforms for error and correct responses across in the high task salience condition for high and low conscientious poor decoders.

The pattern of activity shows little differentiation according to response type and conscientiousness for good decoders (see Figures 24a and 24b). However, conscientiousness levels appear to delineate activity, particularly at frontal sites for poor decoders (see Figure 24c and 24d). Coronal differences are also apparent at frontal sites, with left coronal activity showing larger positivity than right, again with a delineation of activity in terms of Conscientiousness levels for poor decoders only.

### Electrophysiological Analyses

A comparison of mean amplitude was completed for ERN/Ne and CRN, early Pe and Pc, and late Pe and Pc, in order to determine whether overall error and correct response-related activity were significantly different. The five-way ANOVA

conducted on ERN/ Ne and CRN mean amplitude data revealed no significant main effects or interactions involving Response Type ( $ps > .05$ ).

The five-way ANOVA conducted on early Pe and Pc mean amplitude data showed that early Pe ( $M = 2.43$ ,  $SE = 0.52$ ) tended to be more positive than early Pc ( $M = 1.81$ ,  $SE = 0.46$ ),  $F(1, 33) = 4.02$ ,  $MSE = 9.20$ ,  $p = .05$ ,  $\eta p^2 = .11$ .

The five-way ANOVA conducted on late Pe and Pc mean amplitude data revealed no significant main effects or interactions involving Response Type ( $ps > .05$ ).

A separate analysis of each response-related component (ERN/Ne and CRN, and early and late Pe and Pc) was completed and is presented below.

### **ERN/Ne**

A four-way ANOVA conducted on ERN/Ne mean amplitude data revealed a trend approaching significance for a Sagittal Site  $\times$  Conscientiousness interaction,  $F(1, 33) = 3.49$ ,  $MSE = 1.15$ ,  $p = .07$ ,  $\eta p^2 = .10$ ,  $\epsilon = 1$  (see Figure 25). While Tukey post hoc tests did not reveal any significant differences ( $ps > .05$ ), Figure 25 shows that high conscientious participants displayed larger mean ERN/Ne at Fz than low conscientious participants and this pattern was in the opposite direction at FCz. Low conscientious participants demonstrated larger mean ERN/Ne at FCz than Fz while high conscientious participants demonstrated larger mean ERN/Ne at Fz than FCz. No other main effects or interactions reached significance.

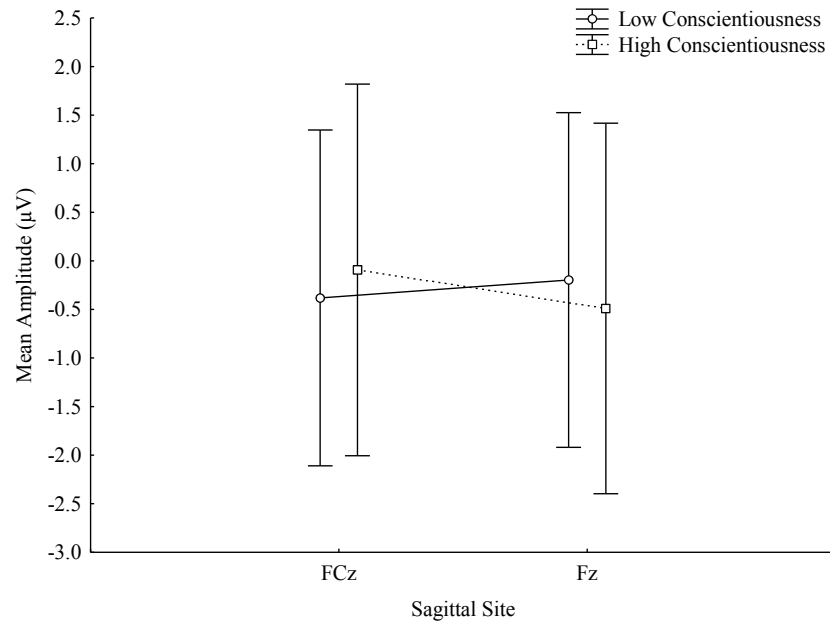


Figure 25. ERN/Ne mean amplitude for high and low conscientious participants at FCz and Fz (vertical bars denote 0.95 confidence intervals).

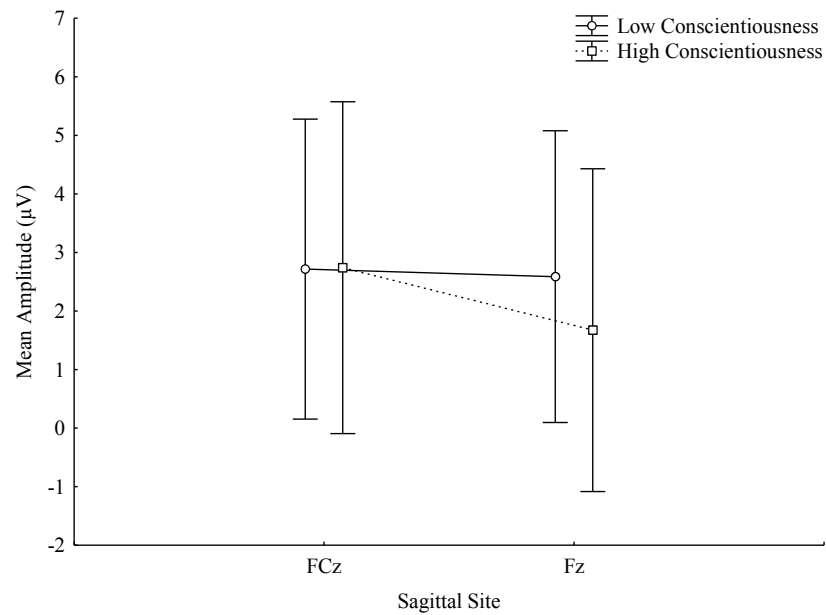
### CRN

No significant main effects or interactions were evident following the four-way ANOVA conducted on CRN mean amplitude data ( $ps > .05$ ).

### Early Pe

The four-way ANOVA conducted on early Pe mean amplitude data revealed a significant main effect of Sagittal Site,  $F(1, 33) = 8.68$ ,  $MSE = 1.97$ ,  $p = .006$ ,  $\eta^2 = .21$ , which was modified by a Sagittal Site  $\times$  Conscientiousness interaction,  $F(1, 33) = 5.32$ ,  $MSE = 1.97$ ,  $p = .03$ ,  $\eta^2 = .14$  (see Figure 26). Tukey post hoc tests indicated that mean amplitude was significantly larger at FCz than Fz for high conscientious participants only ( $p < .01$ ). While no other comparison reached significance ( $ps > .05$ ), Figure 26 indicates that there is little difference in early Pe mean amplitude at FCz for either low or high conscientious participants, but at Fz low conscientious

participants demonstrated larger early Pe mean amplitude compared to high conscientious participants.



*Figure 26.* Early Pe mean amplitude for high and low conscientious participants at FCz and Fz (vertical bars denote 0.95 confidence intervals).

A trend approaching significance for a main effect of Task Salience was also evident following this analysis,  $F(2, 66) = 2.64$ ,  $MSE = 6.75$ ,  $p = .07$ ,  $\eta p^2 = .07$ ,  $\varepsilon = 1$ . While Tukey post hoc tests did not reveal any significant differences, mean amplitude in the moderate task salience condition ( $M = 3.04$ ,  $SE = .62$ ) was more positive than both the low ( $M = 2.12$ ,  $SE = .61$ ) and high task salience conditions ( $M = 2.12$ ,  $SE = .53$ ). No other main effects or interactions reached significance.

### Early Pc

The four-way ANOVA conducted on early Pc mean amplitude data showed that mean amplitude was significantly larger at FCz ( $M = 2.17$ ,  $SE = 0.47$ ) than at Fz ( $M = 1.45$ ,  $SE = 0.47$ ),  $F(1, 33) = 14.66$ ,  $MSE = 1.70$ ,  $p < .001$ ,  $\eta p^2 = .31$ . No other main effects or interactions reached significance.

## Late Pe

The four-way ANOVA conducted on late Pe mean amplitude data revealed a trend approaching significance for a Task Salience  $\times$  Sagittal Site interaction,  $F(2, 66) = 2.92$ ,  $MSE = 0.25$ ,  $p = .06$ ,  $\eta^2 = .08$ ,  $\epsilon = 1$ , (see Figure 27).

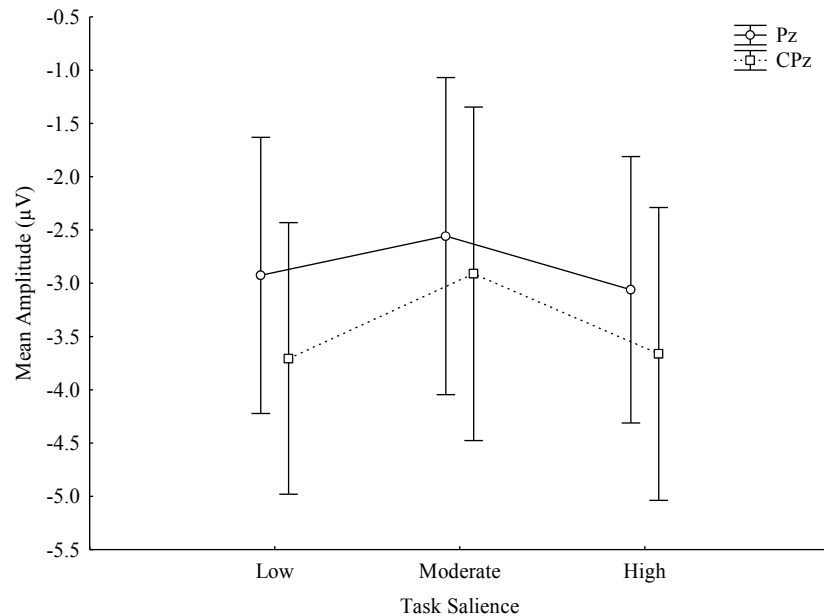
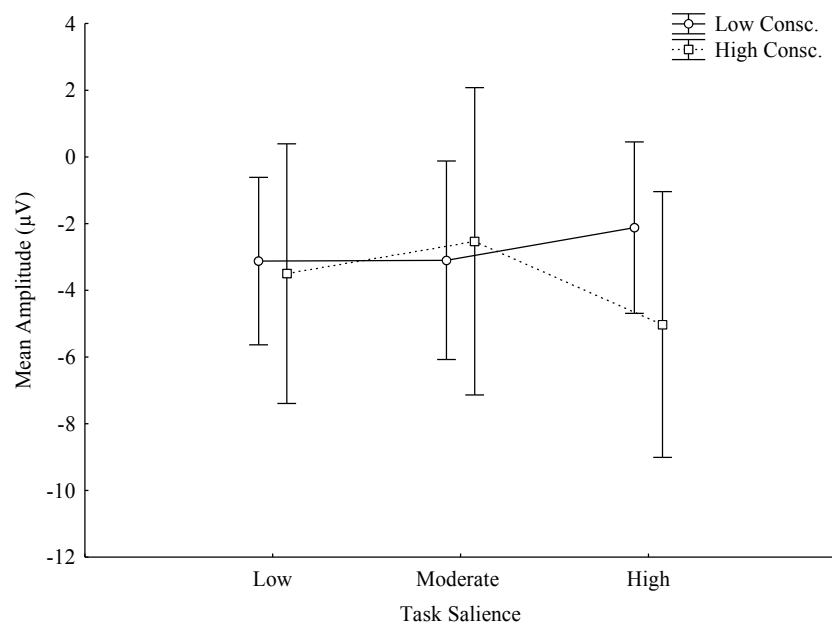


Figure 27. Late Pe mean amplitude at Pz and CPz in low, moderate and high task salience conditions (vertical bars denote 0.95 confidence intervals).

Tukey post hoc tests indicated that at CPz, late Pe mean amplitude in the moderate task salience condition was significantly more positive in the low task salience condition ( $p < .001$ ). While no other comparisons reached significance ( $ps > .05$ ), Figure 27 shows that overall late Pe mean amplitude was larger at Pz than CPz, but the differences were largest in the low task salience condition followed by the high task salience condition, with the smallest difference occurring in the moderate task salience condition.

A Task Salience  $\times$  Decoding Ability  $\times$  Conscientiousness interaction trend was also apparent following analysis,  $F(2, 66) = 2.95$ ,  $MSE = 7.39$ ,  $p = .06$ ,  $\eta^2 = .08$ ,  $\epsilon = 0.95$ . This was followed up with separate 2 [Conscientiousness; low, high]  $\times$  3 (Task

Salience: low, moderate, high) mixed measures ANOVAs for poor and good decoders. Analysis of late Pe mean amplitude for poor decoders revealed no significant main effects or interactions ( $ps > .05$ ); however a significant Task Salience  $\times$  Conscientiousness interaction,  $F(2, 30) = 4.46$ ,  $MSE = 11.39$ ,  $p = .02$ ,  $\eta^2 = .23$ ,  $\epsilon = 1$  (see Figure 28), was evident for good decoders. Although no comparison reached significance following post hoc tests ( $ps > .05$ ), the graph indicates that little difference was apparent in mean amplitude for high and low conscientious participants in the low and moderate task salience conditions yet the high task salience condition clearly differentiated levels of conscientiousness with low conscientious participants demonstrated larger mean positivity than high conscientious participants.



*Figure 28.* Late Pe mean amplitude for low and high conscientious good decoders in low, moderate and high task salience conditions (vertical bars denote 0.95 confidence intervals).



Late Pe mean amplitude remained generally undifferentiated across task salience conditions for low conscientious participants. However, high conscientious participants demonstrated an increased late Pe mean amplitude from low to moderate task salience conditions but this activity was at its most negative in the high task salience condition. No other main effects or interactions reached significance.

### **Late Pc**

The four-way ANOVA conducted on late Pc mean amplitude data showed that mean amplitude was significantly more positive at Pz ( $M = -3.36$ ,  $SE = 0.58$ ) than at CPz ( $M = -4.17$ ,  $SE = 0.62$ ),  $F(1, 33) = 6.59$ ,  $MSE = 4.70$ ,  $p = .01$ ,  $\eta^2 = .17$ . No other main effects or interactions reached significance.

### **Response Awareness**

The analyses of data associated with response awareness are presented below. A separate analysis of data associated with error responses only was conducted due to computer programming constraints which precluded analysis of correct response-related data. Conscientiousness was not examined in terms of response awareness because group numbers were too small to analyse validly.

### **Behavioural analyses**

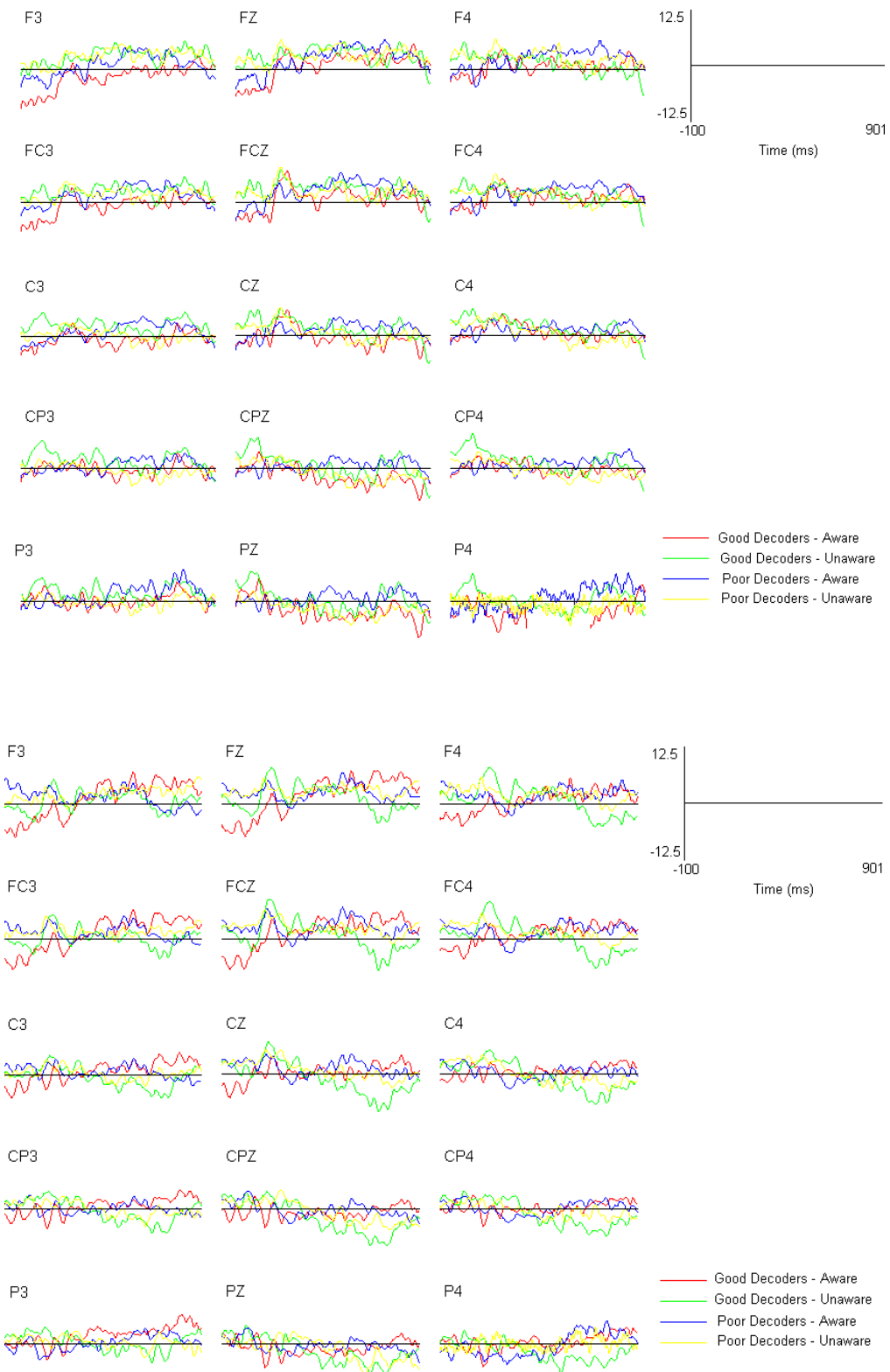
The three-way ANOVA conducted on reaction time data revealed a significant main effect of Task Salience  $F(2,18) = 4.16$ ,  $MSE = 66863$ ,  $p = .03$ ,  $\eta^2 = .30$ ,  $\epsilon = .92$ . Tukey post hoc tests indicated that mean reaction time to stimuli in the low task salience condition ( $M = 1357.29$ ,  $SE = 87.46$ ) was significantly faster than that in the high task salience condition ( $M = 1131.79$ ,  $SE = 62.75$ ,) ( $p < .05$ ), but not significantly faster than the moderate task salience condition ( $M = 1231.39$ ,  $SE =$

70.80) ( $p > .05$ ). Likewise reaction time in the moderate task salience condition was not significantly different from that in the high task salience condition ( $p > .05$ ). No further main effects or interactions within the analysis of reaction time data reached significance.

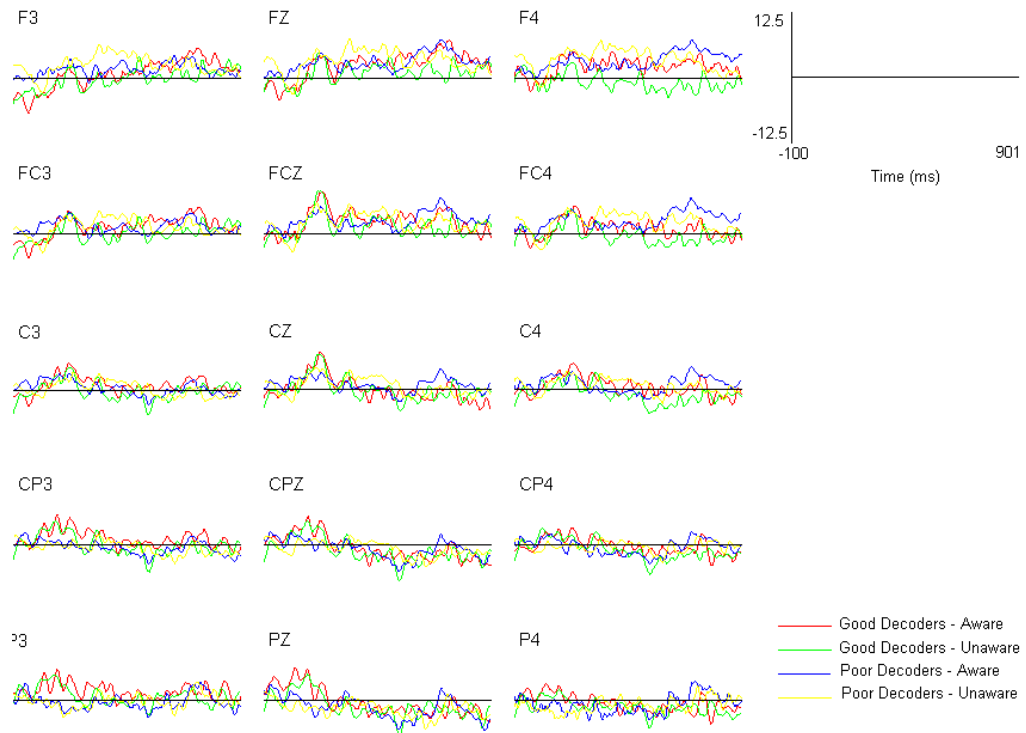
The three-way ANOVA conducted on accuracy data revealed no significant main effects or interactions ( $ps > .05$ ).

### **Grand mean averages**

Grand mean average waveforms were obtained for error responses in the low, moderate and high task salience conditions, and these were broken down by levels of participants' awareness to their response (aware/unaware). Figures 29a and 29b show little delineation across salience conditions and levels of response awareness. An early positive peak is evident frontally and fronto-centrally that, as with the overall grand means, occurs approximately 100 – 120 ms post response. A later slow-going wave is also evident although there appears little difference in amplitude as the activity is considered frontally through to parietal regions.



*Figure 29a.* Grand mean average waveforms for error responses made by poor and good decoders when they were aware and unaware of their responses in low (top panel) and moderate (bottom panel) task salience conditions.



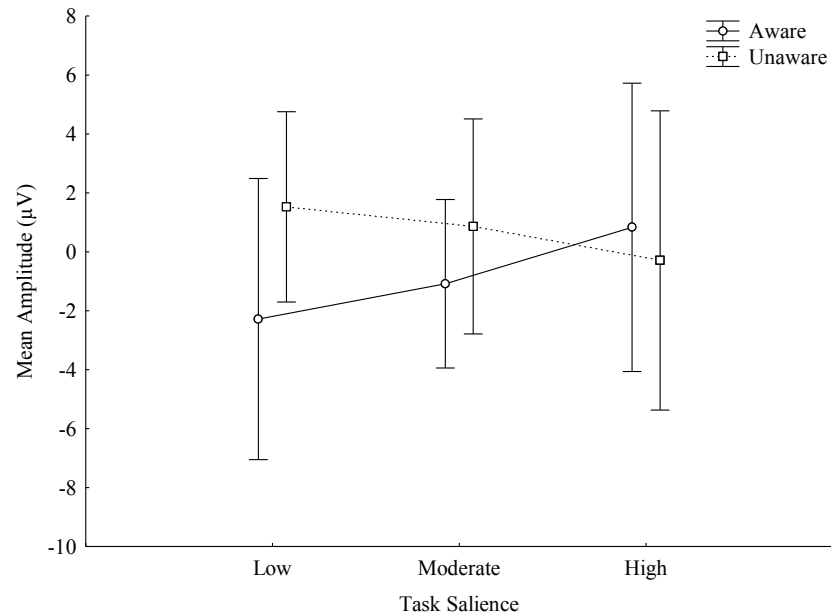
*Figure 29b.* Grand mean average waveforms for error responses made by poor and good decoders when they were aware and unaware of their responses in the high task salience condition.

## Electrophysiological analyses

### ERN/Ne

The four-way ANOVA conducted on ERN/Ne mean amplitude data in terms of response awareness revealed a significant Response Awareness  $\times$  Task Salience interaction,  $F(2, 18) = 3.83$ ,  $MSE = 17.67$ ,  $p = .04$ ,  $\eta^2 = .30$ ,  $\epsilon = 1$  (see Figure 30). While Tukey post hoc tests failed to reveal any significant differences between individual means ( $ps > .05$ ), Figure 30 indicates that ERN/Ne mean amplitude increased in negativity across low, moderate and high task salience conditions when participants were aware of their responses. Conversely, when participants were unaware of their responses, ERN/Ne mean amplitude was reduced according to

levels of task salience, low to high. No other main effects or interactions reached significance.

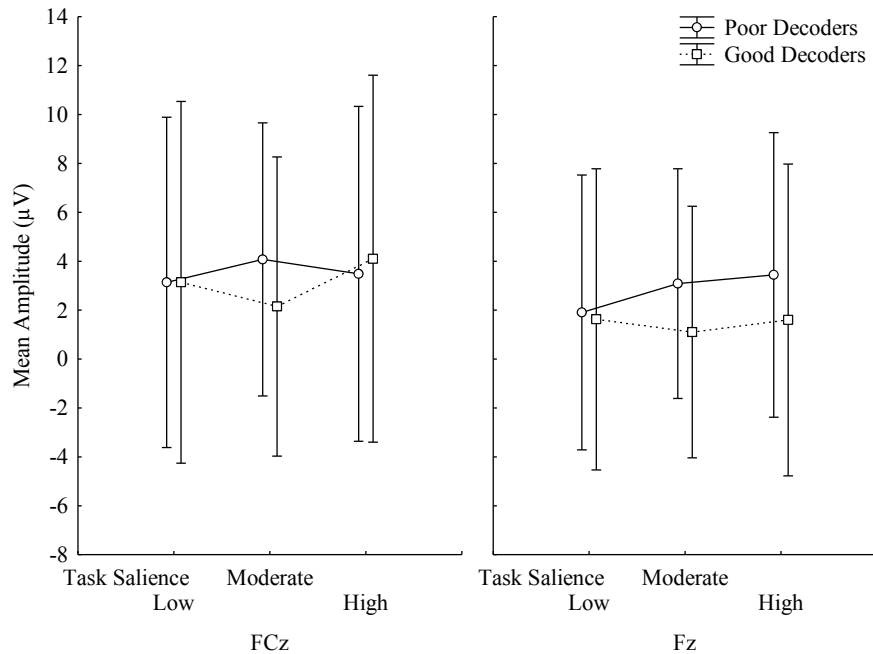


*Figure 30.* ERN/Ne mean amplitude in low, moderate and high task salience conditions for aware and unaware responses (vertical bars denote 0.95 confidence intervals).

### Early Pe

The four-way ANOVA conducted on early Pe mean amplitude data revealed a main effect of Sagittal Site,  $F(1, 9) = 6.17$ ,  $MSE = 7.92$ ,  $p = .03$ ,  $\eta^2 = .41$  which was modified by a Task Salience  $\times$  Sagittal Site  $\times$  Decoding Ability interaction,  $F(2, 18) = 3.75$ ,  $MSE = 1.29$ ,  $p = .04$ ,  $\eta^2 = .29$ ,  $\epsilon = 1$  (see Figure 31). Breakdown analysis at each sagittal site revealed no significant simple main effects or interactions ( $ps > .05$ ). However, Figure 31 indicates that at FCz there appears to be little difference in mean amplitude for poor and good decoders in the low and high task salience conditions, yet in the moderate task salience condition poor decoders displayed larger mean positive amplitude than good decoders. At Fz mean amplitudes mirrored those at FCz in the low and moderate task salience conditions while in the high salience condition

poor decoders displayed larger mean amplitudes than good decoders. No other main effects or interactions reached significance.

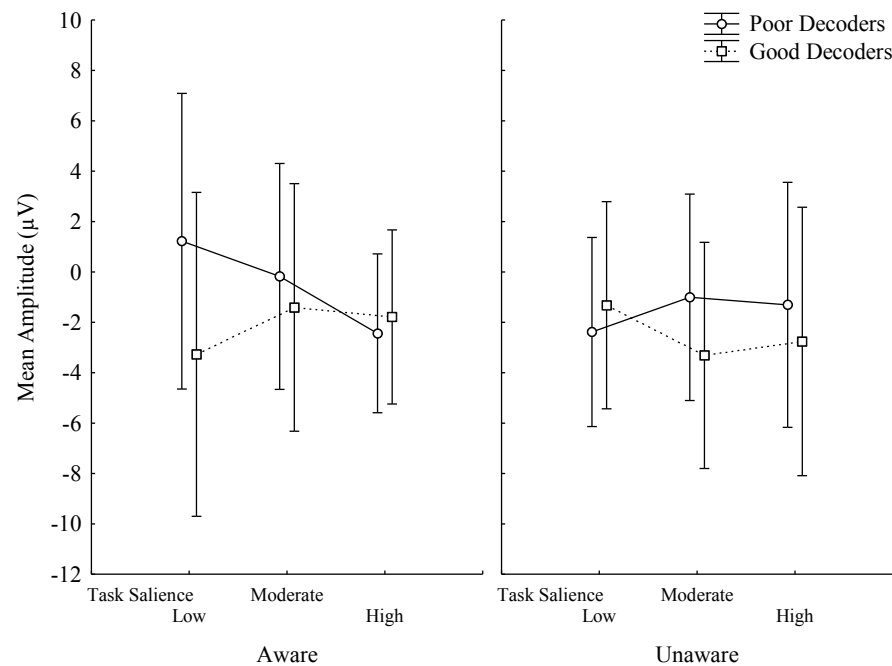


*Figure 31.* Early Pe mean amplitude in low, moderate and high task salience conditions for poor and good decoders at FCz and Fz (vertical bars denote 0.95 confidence intervals).

### Late Pe

The four-way ANOVA conducted on late Pe mean amplitude data revealed a significant Response Awareness  $\times$  Task Salience  $\times$  Decoding Ability interaction,  $F(1, 18) = 6.44$ ,  $MSE = 7.32$ ,  $p = .008$ ,  $\eta p^2 = .42$ ,  $\epsilon = 1$ , (see Figure 32). While Tukey post hoc tests showed no significant differences ( $ps > .05$ ), Figure 32 shows that in aware conditions poor and good decoders were differentiated according to task salience. Late Pe mean amplitude decreased according to task salience for poor decoders and amplitude generally increased according to task salience for good decoders. Poor decoders demonstrated larger late Pe mean amplitude than good decoders in the low task salience condition and this difference was reduced in the

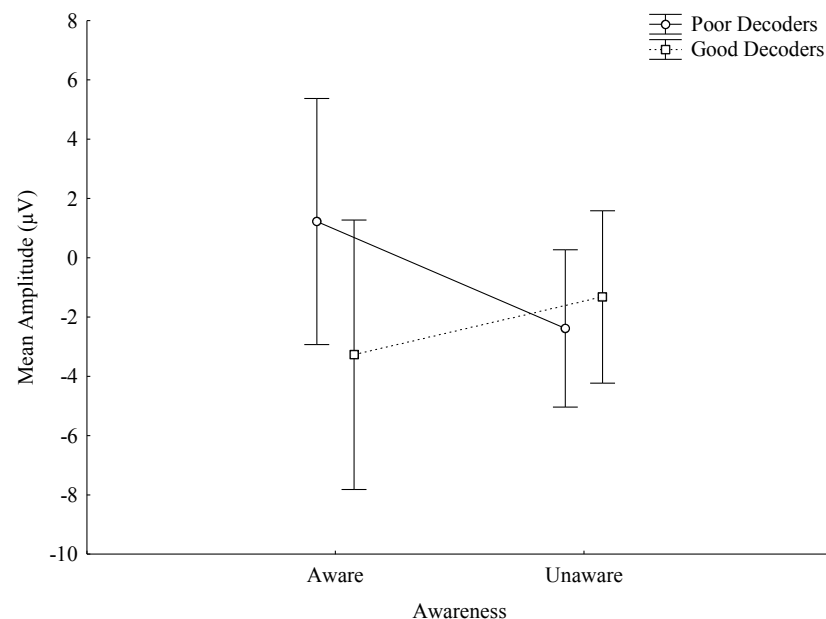
moderate task salience condition. In the high task salience condition good decoders demonstrated larger late Pe mean amplitude than poor decoders. The pattern of activity was generally in the opposite direction in the unaware condition. Poor decoders showed a general increase in late Pe mean amplitude according to task salience and good decoders showed a decrease. Differences between good and poor decoders were largest in moderate and high task salience conditions, with poor decoders demonstrating a larger positivity than good decoders. However, in the low task salience condition good decoders demonstrated larger positivity than poor decoders.



*Figure 32.* Late Pe mean amplitude in low, moderate and high task salience conditions for poor and good decoders in aware and unaware conditions (vertical bars denote 0.95 confidence intervals).

Following post hoc analysis, breakdown analyses were conducted for each level of Task Salience. The 2 [Decoding Ability: poor, good]  $\times$  2 (Response Awareness: aware, unaware) mixed measures ANOVAs revealed no significant

differences within the moderate and high task salience conditions but a significant Response Awareness  $\times$  Decoding Ability interaction within the low task salience condition was found,  $F(1, 9) = 6.89$ ,  $MSE = 6.11$ ,  $p = .03$ ,  $\eta p^2 = .43$  (see Figure 33). While Tukey post hoc tests indicated no significant differences between individual means ( $ps > .05$ ), Figure 33 indicates that poor decoders who were aware of their responses showed larger mean positivity than good decoders who were aware of their responses, while there was little difference in mean amplitude between poor and good decoders when they were unaware of their responses. Overall, poor decoders displayed larger positivity in the aware condition than the unaware condition; however mean amplitude amongst good decoders showed a pattern of activity in the opposite direction with larger mean positivity in the unaware condition compared to the aware condition.

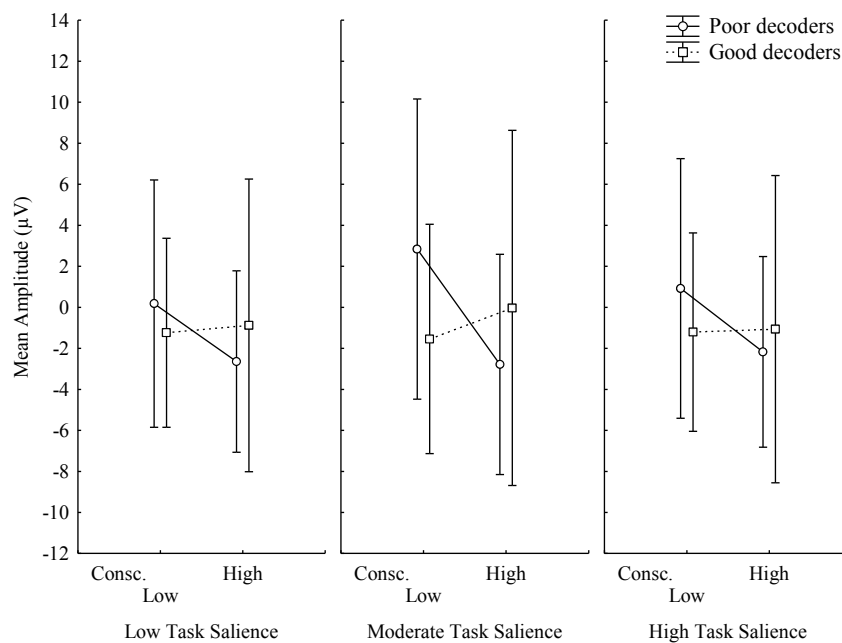


*Figure 33.* Late Pe mean amplitude for poor and good decoders in aware and unaware conditions (vertical bars denote 0.95 confidence intervals).



## Hemispheric Differences

Grand mean averages showed clear coronal differences in the 300 – 600 ms post response time window at frontal sites for both error and correct responses and an analysis of this activity was undertaken. The five-way ANOVA conducted on frontal late Pe and Pc mean amplitude data revealed a significant Task Salience  $\times$  Decoding Ability  $\times$  Conscientiousness interaction,  $F(2, 66) = 6.13$ ,  $MSE = 6.67$ ,  $p = .004$ ,  $\eta p^2 = .16$ ,  $\varepsilon = 1$  (see Figure 34). A breakdown analysis of the Decoding Ability  $\times$  Conscientiousness interaction at each level of Task Salience was conducted.

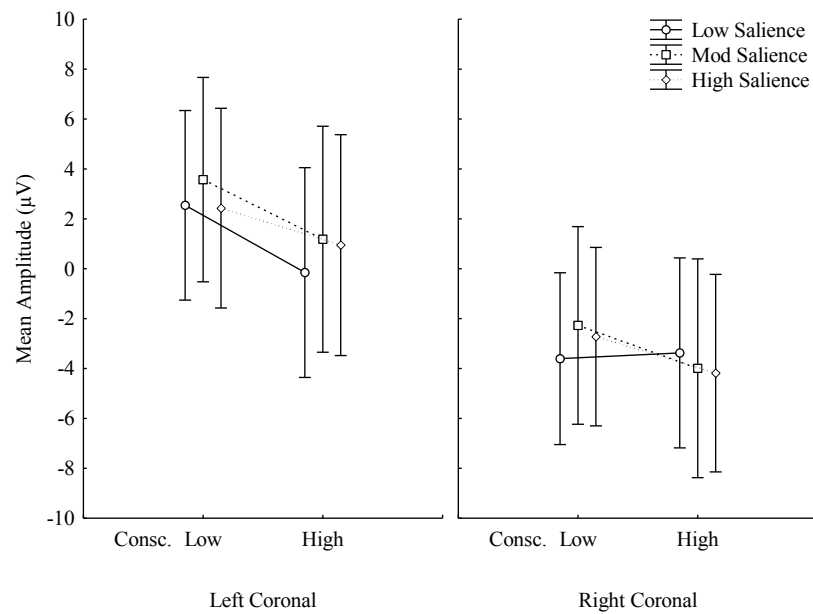


*Figure 34.* Mean amplitude for low and high conscientious good and poor decoders in low, moderate and high task salience conditions (vertical bars denote 0.95 confidence intervals).

A significant Decoding Ability  $\times$  Conscientiousness interaction was found for the moderate task salience condition only,  $F(1, 33) = 4.47$ ,  $MSE = 22.64$ ,  $p = .04$ ,  $\eta p^2 = .12$  (see Figure 34, middle panel). While Tukey post hoc tests did not reveal any significant differences ( $ps > .05$ ), low conscientious poor decoders showed larger positivity than high conscientious, poor decoders and low conscientious, good

decoders. Additionally, high conscientious good decoders showed larger positivity than low conscientious, good decoders and high conscientious poor decoders. Mean amplitude differences between poor and good decoders in the low and high task salience conditions occurred in a similar direction to that in the moderate task salience condition; however the differences were much less pronounced between low conscientious poor and good decoders. High conscientious poor and good decoders in the high task salience condition were less differentiated than the low and moderate task salience conditions respectively.

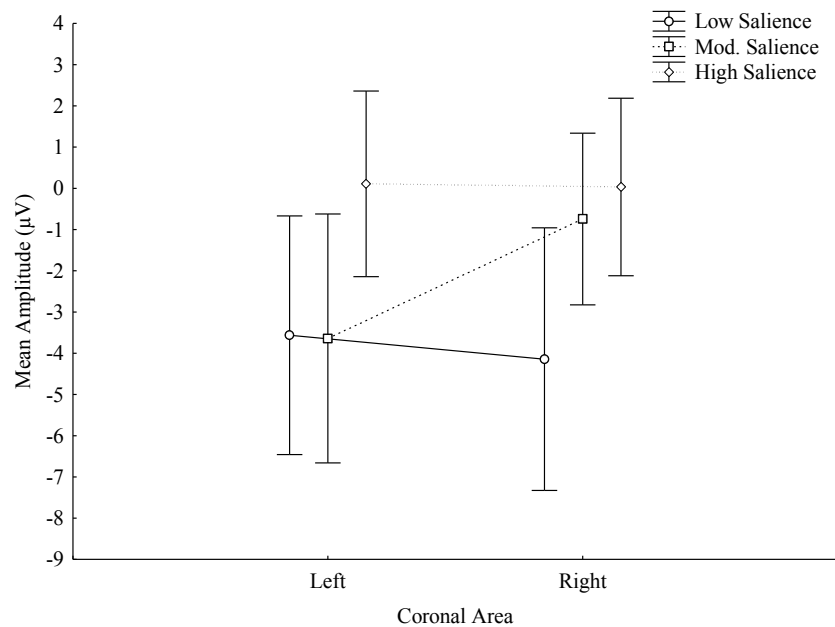
The analysis also revealed a significant main effect of Coronal Area,  $F(1, 33) = 17.21$ ,  $MSE = 144.82$ ,  $p < .001$ ,  $\eta^2 = .16$ , which was modified by a significant Task Salience  $\times$  Coronal Area  $\times$  Conscientiousness interaction,  $F(2, 66) = 3.96$ ,  $MSE = 4.66$ ,  $p = .02$ ,  $\eta^2 = .11$  (see Figure 35).



*Figure 35.* Mean amplitude for low and high conscientious participants in low, moderate and high task salience conditions across left and right coronal areas (vertical bars denote 0.95 confidence intervals).

Breakdown of this three-way interaction by Conscientiousness level revealed a significant main effect of Task Salience for high conscientious participants,  $F(2, 34) = 6.14$ ,  $MSE = 22.74$ ,  $p = .005$ ,  $\eta^2 = .27$ . Tukey post hoc tests indicated that mean amplitude was significantly more positive in the high task salience condition ( $M = 0.07$ ,  $SE = 1.02$ ), than the moderate ( $M = -2.19$ ,  $SE = 0.82$ ) and the low task salience ( $M = -3.85$ ,  $SE = 1.42$ ) conditions while low and moderate task salience conditions did not significantly differ from each other.

Analysis of data associated with low conscientious participants revealed a significant main effect of Task Salience,  $F(2, 36) = 14.41$ ,  $MSE = 24.97$ ,  $p < .001$ ,  $\eta^2 = .44$  and a significant main effect of Coronal Area,  $F(1, 18) = 11.83$ ,  $MSE = 9.06$ ,  $p = .003$ ,  $\eta^2 = .40$ . However, these main effects were modified by a significant Task Salience  $\times$  Coronal Area interaction,  $F(2, 36) = 7.99$ ,  $MSE = 12.96$ ,  $p = .001$ ,  $\eta^2 = .31$  (see Figure 36).



*Figure 36.* Mean amplitude for low conscientious participants in low, moderate and high task salience conditions across left and right coronal areas (vertical bars denote 0.95 confidence intervals).

As can be seen in Figure 36, and confirmed by Tukey post hoc tests mean amplitude was significantly more positive in the high salience than in the low salience condition ( $p < .001$ ), and did not differ coronally within each of these conditions ( $ps > .05$ ). In contrast, activity in the moderate salience condition was significantly more positive in the right area ( $p < .001$ ), which did not differ from the high salience condition, than in the left area, which did not differ from the activity in the low salience condition ( $ps > .05$ ).

### **Discussion**

Contrary to expected outcomes there were no significant differences evident between error and correct response mean amplitudes. On the other hand, predictions in terms of task salience were partially supported. More specifically, the effects of task salience were moderated by response awareness in early negative response-related components and task salience effects were evident in later response-related components. The hypothesis regarding Pe as a reflection of conscious error awareness was not supported. Conscientiousness levels were not found to explicitly moderate sensitivity to task salience; however when considered in terms of decoding ability, differential effects of task salience were found. In light of the language based task used in this experiment, the hemispheric differences evidenced were not as expected.

Early negativities showed no significant differences in mean amplitudes between error and correct responses, which is a finding that is contrary to many investigations of the ERN/Ne and CRN, and the findings of Experiments 1 and 2. Contemporary researchers have generally found amplitudes associated with error responses to be larger than that associated with correct responses when investigating non-clinical samples (e.g., Falkenstein et al., 2000, 2004a; Hajcak et al., 2005). The

investigation of response-related components using language-based tasks, and in particular phonological decoding tasks, is in its early stages with just two groups of researchers, for the most part, reporting typical ERN/Ne and CRN differences when phonological decision tasks were used (Horowitz-Kraus & Breznitz, 2008; Sebastian-Gallés et al., 2006). The task used in the current study was somewhat different to that used by Horowitz-Kraus and Breznitz in that it required participants to consider a two-part stimulus rather than a single word and corresponding decision. This suggests that the lack of difference between ERN/Ne and CRN in the current study may be attributable to a task-specific factor.

Interestingly, Sebastian-Gallés et al. (2006) noted no significant amplitude differences between ERN/Ne and CRN in a group of Spanish dominant speakers when asked to identify Catalan-specific changes to non-words. They argued that the changes may have impacted the certainty with which the stimuli are viewed and evaluated, and this may be reflected in increased CRN amplitudes. Similarly, Pailing and Segalowitz (2004b) found that error and correct response-related activity was similar in the presence of uncertainty and that increased uncertainty resulted in enhanced CRN amplitudes. This points to a possible explanation of the lack of differences noted in early response-related components in the current study. The phonological decision task which included the presentation of two nonwords in each trial may have decreased discriminability of the stimuli and increased uncertainty which in turn impacted overall CRN amplitude. Such an outcome can be explained in terms of an error detection hypothesis (Falkenstein et al., 1991; Scheffers & Coles, 2000) where the ERN/Ne and CRN are a reflection of a mismatch between actual and required responses, with amplitude variations indexing the level of mismatch according to certainty of responses. As Pailing and Segalowitz (2004b) point out the

processes involved in response monitoring may be contingent on the subjective experience of the individual. With this in mind and since error rates for this task were quite high (ranging from 20% to 50%); the overall difficulty of the task may have impacted the subjective certainty of responses. However, in their study considering task difficulty across versions of a flanker task, Pailing and Segalowitz (2004b) found that task difficulty did not influence ERN/Ne amplitudes. They do, however, go on to suggest that very difficult tasks may change the subjective salience of errors and lead to the extrinsic attribution of fault in terms of performance outcomes that may be reflected in amplitude changes in early negative response-related components.

Early and late Pe revealed task salience effects, albeit based on trends. Whereas high task salience differentiated high and low conscientious good decoders in terms of late Pe amplitude, poor decoders demonstrated no effect of either task salience or conscientiousness. While interpretation is approached cautiously, this suggests that the impact of motivation on tasks and the salience effect extends beyond the early negative components, as noted by Hajcak et al. (2005). Although not expressly providing support for Ridderinkhof et al.'s (2009) contention that the early Pe reflects the motivational significance of errors, it does suggest that later components may be similarly influenced by motivational significance.

ERN/Ne amplitudes were found to be differentially influenced by Response Awareness and Task Salience within the early time window. While comparisons of individual means did not reach significance there was an increase in mean ERN/Ne amplitude with increasing task salience for trials when participants were unaware of their responses. This pattern of activity occurred in the opposite direction when participants were aware of their responses. Although it is difficult to make any

conclusive inferences from these findings since the sample sizes were quite small, there is some indication that, consistent with Scheffers and Coles' (2000) findings, awareness of responses may influence early ERN/Ne amplitudes. However, it is unclear why this activity would be differentially impacted according to awareness of error responses only. If salience of tasks and responses plays a role in response evaluation processes, as argued by Hajcak et al. (2005), then it was expected that ERN/Ne amplitude would be largest in high, lower in moderate and reduced further in low task salience conditions. It is not clear why this pattern of activity only occurred when participants were not aware of their error response. Perhaps, when participants were aware of their errors, as Pailing and Segalowitz (2004b) suggest, the perceived difficulty of the task impacted the motivational importance of the response to such an extent that participants disengaged with the task and ongoing evaluation of responses, and this was reflected in reduced ERN/Ne amplitudes.

Whereas no effects involving response awareness were found for the early Pe component, thus not supporting an explanation of this component in terms of conscious error recognition, task salience effects were evident. This finding supports the suggestion by Hajcak et al. (2005) that the influence of task or response salience may extend beyond early response-related negativities. The salience effect was, however, differentiated by decoding ability. At the frontal midline site Pe mean amplitude was relatively stable across salience conditions for good decoders whereas amplitude increased according to task salience levels for poor decoders. This offers some support to Ridderinkhof et al.'s (2009) argument that the Pe is a P3-like component reflecting the ongoing processing of motivationally significant events. Task-specific factors may offer an explanation as to why the task salience effect was only evident in poor decoders. Errors may not be as motivationally salient to good

decoders when completing phonological decision tasks since they may be able to complete future tasks more accurately than poor decoders. Again, this is a cautious interpretation in light of small sample sizes and no significant differences in terms of behavioural data between good and poor decoders.

A response awareness effect was evident for the late Pe; however this was only evident in the low task salience condition. While post hoc tests showed that individual comparisons of means did not reach significance, poor decoders displayed larger mean amplitude than good decoders when aware of their error response with very little difference in mean amplitude evident between decoding groups when participants were unaware of their errors. It is difficult to reconcile this outcome within the confines of the theoretical framework of this thesis and is perhaps suggestive of an outcome driven by small sample sizes.

Low conscientious, good decoders showed larger Pe mean amplitude than high conscientious good decoders in the high task salience condition, with little amplitude difference evident in low and moderate task salience conditions. Overall, activity was negative in amplitude, however late response-related components are generally referred to as positive, as such any differences are interpreted in terms of positive changes or differences. While this finding is based on a trend and should be interpreted cautiously, it may indicate again, that individual differences play a role in overall response evaluation processes. Endrass et al. (2007) suggested that the late Pe might reflect the time course of the effects of conscious error recognition. Since low conscientious individuals were expected to be more susceptible to task salience manipulations (Pailing & Segalowitz, 2004a) the larger positive amplitude displayed by low conscientious compared to high conscientious good decoders might reflect the impact of a recognised important or high value error.



Since past research has determined differential hemispheric processing in terms of stimulus evaluation for good and poor decoders (Martin et al., 2006), and grand mean differences revealed clear coronal differences at frontal sites within the late 300 – 600 ms post response time window, this provided an opportunity to examine the task-specific nature of late response-related components. Whereas good decoders showed little differentiation in mean amplitude across task salience conditions irrespective of levels of conscientiousness, low conscientious poor decoders showed increased positivity compared to high conscientious poor decoders across task salience conditions. This difference reached significance in the moderate task salience condition only, although the pattern nevertheless suggests that underlying individual differences in personality traits, in particular conscientiousness, may moderate later response evaluation processes. Leuthold and Sommer (1999) suggested that Pe amplitude was influenced by an individual's ability to discriminate stimulus properties. It would seem reasonable that poor decoders would find discriminating between a pseudohomophone and non word in a phonological decision task difficult and it could be argued that evidenced higher late positivity for low compared high conscientious individuals might reflect this. However, this may in fact, represent overall disengagement in a task that is considered too difficult, since good decoders irrespective of conscientiousness demonstrated similar component amplitudes. The overall finding that late response-related activity was larger in the left compared to the right hemisphere again suggests that this activity is influenced by specific task related factors since evidence from past investigations of stimulus-related components using phonological decision tasks has also shown differential activity according to coronal site (Martin et al., 2006). This also suggests

(see also Ganushchak & Schiller, 2008) that explanations of stimulus-related components may also inform and guide explanations of response-related activity.

On the whole, no significant differences in ERN/Ne and CRN mean amplitude were found suggesting that early response-related components may be impacted by task difficulty or stimulus discriminability (Coles et al., 2001; Pailing & Segalowitz, 2004b). While response awareness effects were evident in early negativities and late positivities, small sample sizes precluded definitive interpretation of these findings. Also early negativities were found to be impacted by conscientiousness suggesting individual differences that influence goal directed behaviour should be considered in overall explanations of response- and error-monitoring processes. Clear coronal differences in late components indicated differential hemispheric processing in response evaluation. However, this may indicate the influence of task-specific factors since stimulus evaluation processes in phonological decision tasks are also evidenced in differences in hemispheric activity.

## **Chapter 8**

### **General Discussion and Conclusion**

This series of experiments was conducted with the overall aim of investigating the impact of task difficulty, response awareness and individual differences, specifically conscientiousness, on response-related ERP components that are argued to represent performance monitoring and evaluation processes. The literature review provided a summary of a number of hypotheses that have been put forward to explain early negative components (ERN/Ne and CRN) (e.g., mismatch hypothesis (Falkenstein et al., 1990, 1991), reinforcement learning hypothesis (Holroyd & Coles, 2002) and the conflict monitoring hypothesis (Yeung et al., 2004)). Similarly, a variety of diverse explanations of early error-related positivity (Pe) were noted (e.g., error awareness (Falkenstein et al., 2000; Nieuwenhuis et al., 2001), response strategy updating (Hajcak et al., 2003), affective or emotion-related processing (Herrmann et al., 2004) and a P3 like component (Ridderinkhof et al., 2009)). On the other hand, it was observed that later correct-related components (Pc) have received little attention in the literature. Since the discovery of these reliably occurring response-locked ERP components approximately two decades ago (Falkenstein et al., 1990, 1991), a great deal of research focus has been directed towards investigating them and the factors that may influence response-monitoring systems (Inzlicht & Bartholow, 2009). An extensive examination of the research literature has revealed contrasting and inconsistent findings and indicates that simple explanations of response-related ERP components, in terms of error detection or response recognition, are insufficient. To accommodate the variations in results, the potential of task-specific factors, task difficulty and individual differences to moderate these processes must be, at the very least, acknowledged.

The aim of Experiment 1 was investigate and clarify the role task difficulty plays in response evaluation processes, and the way in which individual differences in terms of conscientiousness may influence task-related behaviours and response awareness. Evidence that the ERN/Ne was significantly larger than the CRN indicated that, at a basic level, this activity can be explained within current theories of response monitoring where it is proposed that the components represent a comparative response-evaluation system that detects a disparity between correct and error responses (Falkenstein, 2004a, Falkenstein et al., 1990, 1991).

Experiment 1 provided evidence that, as was argued by Pailing and Segalowitz (2004a), underlying personality traits, in this case conscientiousness, influence response-related activity and thus should be considered in overall explanations of executive processes associated with performance monitoring. Congruency effects were found to be moderated by conscientiousness. Specifically, that no differences in ERN/Ne amplitudes according to congruency levels were seen for high conscientious, and thus intrinsically motivated, individuals suggests that this group may be maximally engaged in task evaluation irrespective of demands. On the other hand, the finding of variation in ERN/Ne amplitudes according to levels of congruency for low conscientious individuals, suggest that these individuals may be motivated to engage in, and evaluate, easier compared to more difficult tasks. That these results were evident for error and not correct responses provides support for the argument that the ERN/Ne and CRN are functionally separable and that, as was pointed out by Hajcak et al. (2005), the ERN/Ne reflects some measure of the motivational salience of errors. The argument that high and low conscientious individuals differentially engage in evaluative processing is further supported by conscientiousness effects evident in early Pe amplitude differences. Larger Pe

amplitudes associated with high conscientious compared to low conscientious individuals may be an indicator that, as Van Lieshout (2000) suggests, high conscientious individuals are more engaged in the regulation of goal-directed behaviour than low conscientious individuals. These results also support Ridderinkhof et al.'s (2009) contention that the Pe reflects the conscious processing of motivationally significant events with highly conscientious individuals impacted by errors to a greater extent than low conscientious individuals. This is reflected in differing Pe amplitudes. These results also suggest that the explanation of motivational salience may extend beyond the ERN/Ne to later response-related components.

Experiment 2 aimed to further clarify the role of task difficulty in response evaluation processes by investigating the effects of increasing task demands, levels of conscientiousness and response awareness on response-related ERP components. The results of Experiment 2 add support to the argument that task difficulty and individual differences that impact goal-directed behaviour interact in some way and may determine how individuals monitor their performance. At one level, the results of Experiment 2 replicated that of Experiment 1, with error responses eliciting larger negative amplitudes than correct responses; however when conscientiousness levels were considered, as was the case in Experiment 1, a more complex picture of response-monitoring emerged. Congruency effects were again found to be moderated by levels of conscientiousness; however in the more demanding four-choice flanker task used in Experiment 2, this effect was focused on correct and not error responses, and occurred in the opposite direction to that evidenced in the less demanding two-choice flanker task. Since the stimuli used in Experiments 2 and 3 were identical, an explanation for these outcomes points toward differential demands or difficulty of

two- and four-choice flanker tasks. Error responses may be less recognisable, and consequently less salient, than correct responses in the more difficult four-choice flanker and as such evaluative processing is focused on correct responses. CRN amplitude differences according to congruency level for high conscientious individuals suggests that evaluative processing in an overall more demanding task is also influenced by task difficulty. This finding indicates that explanations of motivational salience should not be confined to error responses (Hajcak et al., 2005) but extended to correct responses as well. Clear congruency effects evident in later time windows suggest that these components might be feasibly included in overall explanations of response evaluation and processing. Indeed, in this instance such late activity may be an indicator of conscious response evaluation according to task demands, as has been argued by previous researchers (Burgio-Murphy et al., 2007; Endrass et al., 2007). Explanations of variations in response-related components in terms of response awareness in Experiment 2 were again constrained within small sample sizes. However, evidence of awareness effects in early CRN and Pc, while contrary to the prediction that it is Pe that indexes response awareness (Endrass et al., 2005; Nieuwenhuis et al., 2001), suggest that investigations of response monitoring involving certainty or awareness of responses could be extended to that activity associated with correct responses.

Evidence from Experiments 1 and 2 suggests that task demands play a role in response monitoring processes but that the impact of this is moderated by individual differences, particularly conscientiousness. It has been argued that levels of conscientiousness may directly influence how individuals actively engage in task related behaviour (Ashton & Lee, 2001; Van Lieshout, 2000) and in turn may also reflect levels of task or response salience. Thus, Experiment 3 aimed to investigate

task salience through incentives, conscientiousness and response awareness, and the impact of these factors on ERN/Ne, CRN, early Pe and Pc, and late Pe and Pc. The fact that no significant differences were seen in ERN/Ne and CRN amplitudes suggests that task difficulty or stimulus discriminability influences early response-related processes; however outcomes could also have been attributable to task-specific factors associated with a language-based task. This was further supported by evidence of hemispheric differences in response-related components that were similar to that derived from stimulus-locked activity elicited during language tasks (Martin et al., 2006). Evidence in Experiment 3 of a task salience effect in early and late Pe and Pc suggests that motivational salience explanations for ERN/Ne (Hajcak et al., 2005) may also be applied to later components associated with evaluative processes. When individual differences, in terms of conscientiousness, were taken into consideration, evidence of the influence of this factor at early and late evaluative stages again suggests that underlying personality traits, particularly those said to be involved in the regulation of goal-directed behaviour (Van Lieshout, 2000) should be included in explanations of response-related ERP components. Alternatively, when this outcome is considered together with evidence from the previous experiments, a different explanation can be considered. The larger difference between ERN/Ne and CRN amplitudes seen in Experiments 1 and 2 compared to the ERN/Ne – CRN difference in Experiment 3 suggests that the task demands of the phonological decision task (Experiment 3) and two- and four-choice flanker tasks (Experiments 1 and 2) differentially influence response certainty (Pailing & Segalowitz, 2004b) and that this is reflected in ERN/Ne and CRN amplitudes. However, it is noted that this conclusion is based on evidence gathered from fundamentally different tasks and that the disparity in component amplitudes could reflect other task-specific factors.

## **Conclusion**

Performance monitoring is essential to adaptive behaviour and a critical aspect of information processing (Falkenstein et al., 2000; Hajcak et al., 2005; Pailing & Segalowitz, 2004a, 2004b; Ridderinkhof et al., 2009). As such, the ERP components said to represent this process have been widely and vigorously investigated; however models and theories proposed to explain these processes are unable to account for all experimental data (Inzlicht & Bartholow, 2009). The results of the present series of experiments support previous research in providing evidence that response-related processing is more complex than basic error detection or recognition, indeed differences in ERP response-related component amplitudes suggest that these processes are moderated by task related factors such as task difficulty or task specificity and individual differences that may impact task-related and goal-directed behaviour, specifically conscientiousness. Past explanations of ERN/Ne in terms of motivational salience (Hajcak et al., 2005) and underlying personality traits (Pailing & Segalowitz, 2004a) were further supported; however evidence from the current series of experiments suggests that these factors are also implicated in both correct response and later evaluative processing. Indeed, the results indicate that task demands may dictate the type of response, error or correct, that undergoes the evaluative process, which is in turn influenced by the motivational salience of the task. Although some explanations may have benefited from additional information associated with response awareness measures, data limitations precluded examination of this information in these experiments. Nevertheless, this provides a way forward for future researchers to clarify the function of response awareness or response certainty in performance monitoring. In conclusion, both correct and error response mechanisms are clearly task dependent. Behavioural and



electrophysiological changes according to levels of task demands across the series of experiments suggest task difficulty modifies the way in which responses, whether correct or error, are evaluated. Evidence further suggests that conscientiousness interacts with task difficulty and task specific factors to influence the importance of responses that is also reflected in the ERP component amplitudes of response evaluation. The overall findings of the present research indicate that the processes involved in performance monitoring involve a complex interplay of task demands that are played out across a broad time-frame and are best investigated within a framework that includes individual differences that impact motivation, goal-directed behaviour and response salience.

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## **APPENDIX A**

### **The Quantification of ERN/Ne: A comparison of methods**

## **Abstract**

Error negativity (ERN/Ne) is a response-locked event-related potential that occurs following an erroneous response. Considering that the quantification of this component has been approached in differing ways, an investigation and evaluation of the appropriateness of three approaches to quantification was conducted. Using data gathered from a language based task, peak detection, mean amplitude measures, and difference waveforms were assessed. These approaches were also applied to components identified within difference waves that were derived from the subtraction of correct response activity from error response activity where trial numbers were both matched and unmatched. The outcomes of analyses of ERN/Ne measured within a time window 0 to 100 ms post response are quite dissimilar across each of the quantification methods. Since no evidence of similar patterns of significance across or within each method of quantification was found, it was determined that a priori justification of component quantification is a critical element of the analysis process of the ERN/Ne component of ERP data.

The error negativity (Ne) or error-related negativity (ERN) has been described as a response-locked event-related brain potential (ERP) component that occurs approximately 50 to 100 ms following the commission of an error. First observed by Hohnsbein, Falkenstein, and Hoormann (1989), the investigation of ERN/Ne has generated considerable research with explanations of the function of this component emerging from several differing hypotheses. In their conflict monitoring hypothesis, Yeung, Botvinick, and Cohen (2004) proposed that the ERN/Ne reflects the extent of conflict between differing response options. Alternatively, Holroyd and Coles (2002) argue that the ERN/Ne is produced as a result of increased dopaminergic activity during a reinforcement learning process. A further growing body of researchers have reported motivational and affective influences on Ne, suggesting that this negativity reflects more than simply the recognition of an event, rather, it may be an index of the affective response to the event taking place (e.g., Hajcak, Moser, Yeung, & Simons, 2005; Pailing & Segalowitz, 2004).

Once electroencephalographic (EEG) scalp recordings have been collected, a critical part of the process of ERP research involves the scoring or quantification of components (Hoormann, Falkenstein, Schwarzenau, & Hohnsbein, 1998). The quantification of ERN/Ne has been approached in differing ways by different investigators. Peak amplitude and latency analysis within a pre-determined time window, analysis of mean amplitude, and mean area across a specific time window have all been reported. Whereas most authors report the parameters used in the quantification of components, the rationale for the selection of particular parameters and approaches to component scoring is not always clear. It is quite possible that differing methods may result in differing statistical outcomes. Indeed, Overbeek, Nieuwenhuis, and Ridderinkhof (2005) argue that component scoring choices may

markedly change the pattern of results. In a review of literature published on research into the dissociability of ERN/Ne and error positivity (Pe) (a later positive component associated with errors), they report examples where peak amplitude measures and mean amplitude measures result in differing topographic presentations of activity. While acknowledging that differing approaches to the quantification of ERP components are necessary, Overbeek et al. suggest that reporting the justification for choices made in this regard should be a minimum requirement for all authors. Considering this, a comparison and evaluation of three approaches to the quantification of ERN/Ne are presented: peak detection, mean amplitude measures, and difference waveforms.

This examination took place within the context of an experiment investigating the effects of incentive and personality type on ERN/Ne using phonological and lexical decision tasks. Considering the findings of Hajcak, Moser et al. (2005) who found that error activity reflected the salience of responses, it was hypothesised that errors committed within a high task value condition would produce larger error negativity than errors committed within a low task value condition. Also in view of the findings of Pailing and Segalowitz (2004), who found that personality traits impacted the level of incentive or motivational related changes to ERN/Ne amplitude, it was predicted that high conscientious participants would display reduced ERN/Ne amplitudes in high task value conditions compared to low conscientious participants. To the best of the author's knowledge ERN/Ne is yet to be examined using a language based task and the role of decoding ability in error related activity is unknown.

### **Peak Detection**

Peak detection is a commonly used method of ERP quantification and within

ERN/Ne research it has been widely used. Falkenstein, Hoormann, Christ, and Hohnsbein (2000) note that, generally if clear peaks are visible from grand mean averages then peaks are used to quantify amplitude and latency of components. The peak detection method involves scrutinising grand mean average data for each experimental condition and determining a search window in which the peak of interest occurs. This process will usually entail the centring of the peak within the search window and identifying the window margins. Amplitude and latency of the detected peak are then measured from average waveforms for participant data in each experimental condition (Handy, 2005; Hoormann et al., 1998). Considering the possible affective influences on Ne, Compton et al. (2007) used peak detection to quantify the component and from this, amplitude measures were used to investigate differences according to anxiety levels within a postulated error monitoring system. Using a facial expression recognition task and quantifying activity within a time window of 50 ms pre response to 150 ms post response, they found ERN/Ne amplitude was modulated by state anxiety levels and was highest at FCz. No significant difference in ERN/Ne amplitude was evident between Fz and Cz sites. The researchers did not provide information regarding ERN/Ne latency. Ehlis, Herrmann, Bernhard, and Fallgatter (2005) explored the relationship between ERN/Ne and types of errors (internal/personal errors and external/environmental errors) and they also used peak detection to identify and measure ERN/Ne amplitude. Additionally they considered ERN/Ne latency in terms of differing responses to actual errors and responses perceived as errors as a result of experimenter feedback. Using a modified Eriksen Flanker Task and quantifying ERN/Ne within a 30 ms pre response to 150 ms post response window, the researchers found ERN/Ne to only occur when internal, or actual, errors were made while there was no evidence of



ERN/Ne when an external or feedback errors were made. In comparison to the results of Compton et al., ERN/Ne amplitude was found to be significantly more negative and latencies significantly shorter at Cz compared to activity at Fz.

There are several problems associated with peak detection in average waveforms. A fundamental understanding of ERP research is that the voltage measured at the scalp is a summation of intracranial activity; consequently, observed peaks may consist of many source component waveforms that occur within the specified time window. As such, peaks may bear no resemblance to underlying components and the subsequent calculation of peak amplitude may provide a distorted measure of amplitude not associated with individual source components (Luck, 2005). While it is argued that mathematical transformations such as Principal Components Analysis (PCA) or Independent Components Analysis (ICA) can extricate underlying components, the efficacy of this process is impacted by the latency of components. That is, latency variation in one component may result in it being identified incorrectly as several separate components (Hoormann et al. 1998; Möcks, 1986).

A further difficulty with analysis of peaks concerns the interpretation of the time course of components. Similar to the ambiguity of interpretation of peak amplitude, it is difficult to determine the latency of components using the peak detection approach, again because many components with differing latencies may occur within the specified time window (Luck, 2005). This latency jitter occurs when trial-by-trial differences in effort, attention to task, or arousal result in differing component latencies. In the process of deriving average waveforms for individual participants, latency jitter of components may distort the average peak or result in noise peaks being identified as component peaks. Hoormann et al. (1998) point out

that several methods are available to overcome this, such as a Woody filter (Woody, 1967 as cited in Hoormann et al. 1998), single trial analysis, or imposing response time limits on participants; however, the usefulness and applicability of these approaches are limited. In the case of the Woody filter, consideration of possible underlying sub-components is essential. This cross-correlational method of latency estimation uses a measure from a segment of each epoch and correlates this with a template, generally taken from a similar segment from an averaged ERP. This measure may be distorted if there is a disparity in the degree of overlap of any underlying subcomponents (Woody, 1967). Luck also points out the usefulness of this technique is also limited because it is based on a template matching approach that may inadvertently identify noise peaks as those associated with the waveform of interest.

Generally experimental design constrains the use of single trial analysis although this approach may be applicable in experimental designs that use identical stimuli, such as those used in a standard flanker task or oddball task. However, this method is not appropriate in language based tasks where individual trial stimuli differ. The third method which has been proposed to help overcome latency jitter is imposing response time limits which may focus participant effort and reduce possible component jitter; however if these are overly restrictive then this approach introduces a possible stimulus-related component overlap.

As Luck (2005) points out there is another potential issue impacting the use of peak amplitude measurements: generally they are nonlinear. That is, for the most part, the average of peak amplitudes does not equal the peak amplitude of grand average waveforms. Grand average waveforms are computed as a mean of summed participant averaged data and Luck argues that this approach will generally result in

dissimilar measures of peak amplitude compared to data taken from peak measures of overall participant waveforms. This has implications both in the early scoring stages with choices of time windows influenced by distorted grand average waveforms and presentation of grand average waveforms that do not equate to peak amplitude measures that are subsequently submitted to statistical analyses.

The difficulties associated with peak amplitude measures are also reflected in peak latency measures. For example, like peak amplitude measures, they are non-linear, impacted by noise, and do not necessarily equate to underlying component latency (Luck, 2005). Furthermore, in a study considering the efficacy of the measurement of component latency, Gratton, Kramer, Coles, and Donchin (1989) found that the peak detection method of deriving peak latency and subsequent measurement was the least accurate of a range of approaches to signal detection. They point out that the precision of latency measures is directly related to the signal-to-noise ratio; that is, as the signal-to-noise ratio decreases the accuracy of latency estimation increases, and without the application of filters during the collection or editing process latency measures may be quite inaccurate.

Of course, the difficulties associated with peak amplitude and latency measures do not necessarily preclude the use of peak detection and subsequent analysis and while Luck (2005) argues “there is nothing special about the point at which the voltage reaches a ... maximum” (p. 230); measurements of peak amplitude and latency have been the method of choice for many ERP researchers investigating ERN/Ne (e.g., Christ, Falkenstein, Heuer, & Hohnsbein, 2000; Compton et al., 2007; Ehlis et al., 2005; Falkenstein et al., 2000). Indeed, Fabiani, Gratton, and Coles (2000) maintain that with well established and consistent findings across commonly used experimental parameters the use of peak detection is appropriate. Using various

levels of choice reaction time tasks with more common experimental paradigms, such as variations of the Eriksen flanker task, Go No-go, or Stroop tasks, researchers consistently report a negative peak up to approximately 10 micro volts ( $\mu\text{V}$ ) occurring approximately 50-100 ms post response (Bernstein, Scheffers, & Coles, 1995; Falkenstein et al.; Hajcak, McDonald, & Simons, 2004; Inzlicht & Gutsell, 2007; Pailing & Segalowitz, 2004). Falkenstein et al. explain their choice to use peak amplitude and latency as being based on the perusal of grand mean averages and given they were using well established experimental paradigms this seems a reasonable choice. However, since this type of explanation for the choice of analysis occurs in the minority (Overbeek et al., 2005) and there are a wide range of disadvantages associated with peak amplitude and latency measures, a fuller explanation from other authors of the reasons supporting quantification choices would help provide clarity and allow an informed assessment of methodological choices.

On the whole, when using peak detection as a method of ERP quantification and subsequently derived peak amplitude and latency measures it is important to consider the limitations of this method. Whereas it is reasonable to use this approach when working with commonly used experimental tasks that produce recognised and consistent peaks it should be acknowledged that these measures do not necessarily equate to underlying subcomponents, are greatly impacted by noise, and are generally non-linear measures. Accordingly, use of this approach must be carefully considered.

### **Mean Amplitude Measures**

Mean amplitude refers to a measure of the arithmetic average of amplitudes measured at each time point, usually millisecond intervals, within a pre-defined time

window. In a similar manner to the peak detection method, the time window is usually centred on an identified peak or area of interest with time window boundaries set so as to restrict inclusion of time points associated with neighbouring components (Handy, 2005). Using a stop-signal task to investigate error awareness, Endrass, Franke, and Kathmann (2005) quantified activity using mean amplitude measures for ERN/Ne and Pe components. Using a relatively small time window of activity from 70 ms post response to 110 ms post response they found no significant differences between perceived and unperceived errors with overall activity maximal at Fz. Hajcak, Moser et al. (2005) also chose a mean amplitude measure when investigating task value and motivational effects on ERN/Ne using an arrowhead flanker task. Within a larger time window from 0 – 100 ms post response, they found that the ERN/Ne differed significantly according to task value and this activity was focussed at Cz. In both cases mean amplitude measures were chosen despite clearly visible peaks occurring in grand mean average figures published. As with other forms of ERP quantification, mean amplitude has both strengths and weaknesses and these should be considered prior to making a decision to use this approach.

In the first instance, the morphology of the average waveform can guide the decision to take a mean amplitude measure. Generally, if peaks are not well defined and show a flatter appearance as seen for example in slow going ERP components such as contingent negative variation (CNV), it is more appropriate to use a measure of mean amplitude rather than peak amplitude. Yet, mean amplitude measures can, and have been in many cases, applied to measure activity when peaks are apparent (e.g., Endrass et al., 2005; Hajcak, Moser et al., 2005). When using mean amplitude to quantify activity, consideration of overall waveform shape is essential. Onset and offset latency will influence the overall mean amplitude measure and thus affect final

analyses. The use of mean amplitude measures can readily identify differences across experimental conditions when peaks remain similar but onset or offset latencies differ (Handy, 2005). Luck (2005) points out that the use of mean amplitude measures is particularly advantageous and addresses an area of concern often noted in critiques of ERP quantification and measurement. Comparing data across experimental conditions where differing numbers of trials contribute to participant averaged data can impact greatly on overall measures of amplitude. The inclusion of fewer trials in averaged data results in noisier waveforms and this can potentially impact setting time windows or placement of peak amplitude markers. Luck argues that if a measure of mean amplitude is used this is unlikely to have as great an impact and therefore it is acceptable to compare data across conditions when differing numbers of trials contribute to participant averaged data. A further strength of mean amplitude measures is that they are linear. That is, mean amplitude of grand average waveforms across a specified time window will be equal to the mean of the component means of individual participants. Thus, unlike data analysed using peak amplitude and latency measures, grand average waveforms will be an accurate reflection of the mean amplitude data being analysed (Luck, 2005).

The use of mean amplitude measures is not without disadvantage with component latency not readily calculable. This can be problematic when the time course of components is important to the investigation (Hoormann et al., 1998). Luck (2005) suggests that fractional area latency is an approach to calculating latency from mean area measures that may alleviate this concern. Essentially, fractional area latency is calculated from a measure of area under the waveform within a specified time window. The time point at which the area is divided into a specified fraction becomes the latency measure. Fractional area latency is generally set at 50%. That is,

the 50% area latency is that time point at which the area under the waveform is divided in half. This approach is very sensitive to the time window used but it is useful in many ways. It is a linear measure and therefore corresponds to grand mean average waveform representations of data. Fifty percent area latency measures are also less sensitive to noise. This was clearly demonstrated in a simulation of noise added to an averaged waveform across 100 trials (Luck, 2005). As expected, overall analysis revealed that standard deviations of both peak latency and 50% area latency measurements increased with the addition of noise. However, while mean peak latency measures differed with the addition of noise the mean 50% area latency measure remained unchanged (Luck, 2005). Thus this approach provides a functional latency measure for components with a flat morphology or when several similar peaks are evident within a specified time window. Luck also argues that it is a valid and more accurate approach to measuring component latency than that derived from peak measures.

Many researchers have used mean amplitude as a measure of ERN/Ne (e.g., Endrass et al., 2005; Hajcak & Foti, 2008; Hajcak, Moser et al., 2005), and while all usually report how components were defined and relevant mean amplitude parameters, few detail reasons for their choice and this leads to ambiguity in understanding. For example, Hajcak, Moser et al. describes an experiment investigating motivational influences on Ne. They indicate a choice to measure mean amplitude even though peaks are clearly visible on grand means and, while in general terms mean amplitude has many advantages over peak amplitude measures, there is no clear justification for this approach to the measurement of ERN/Ne in this case. These researchers used a well established experimental paradigm, an arrowhead version of the flanker task, stimuli elicited a peak at the time and amplitude

commensurate with other findings, and the authors further noted that following a PCA a single underlying component equivalent to the peak was evident. These points all provide strong cause to undertake a peak amplitude measure and, while it is reasonable to complete an analysis using a measure of mean amplitude, as indeed Hajcak, Moser et al. did, they do not provide a rationale for their choice of quantification method.

Generally, mean amplitude and area latency measures provide an approach to ERP component quantification that can be applied to both peak and flat morphologies. This method is less impacted by noise than the peak detection method and useful when unequal trial numbers are evident across experimental conditions, however, as with peak detection measures, mean amplitude measures are particularly impacted by onset and offset latency jitter.

### **Difference Waveforms**

Subtraction methods are often used in ERP research to isolate components. The process of subtracting average activity associated with one condition from another creates difference waveforms (Fabiani et al., 2000). The lateralised readiness potential (LRP) is also calculated as a difference wave, but in this instance involves calculating differences between activity at differing electrode sites (Hoormann et al., 1998). Falkenstein et al. (1990) used difference waves to establish activity, and then quantify components associated with focused and divided attention and its effects on Ne. Using a letter recognition task across visual and auditory modalities they revealed a response locked fronto-central negativity that was explained as a mismatch between an early executed response and a response selection process that would otherwise produce a correct response. In an initial study investigating their conflict monitoring hypothesis of Ne, Yeung et al. (2004) also used difference



waveforms to represent the activity that was the difference between error and correct responses. In simulation studies using an Eriksen flanker task, they found that activity was larger for congruent than incongruent trials. Hajcak, Holroyd, Moser and Simons (2005), investigating the effect of expectations and feedback on Ne, used difference waveforms to isolate activity differences between positive and negative feedback before quantifying components through a peak detection process. They found that feedback negativity was maximal frontally and centrally compared to parietally but did not differ between frontal and central sites. Hoormann et al. (1998) point out that this method has been used extensively in ERP research, and has the advantage of controlling for activity that is constant across conditions however an underlying assumption associated with the use of difference waveforms is that the common activity across conditions does not vary and this is very difficult to establish (Falkenstein et al., 2000; Hoormann et al.; Luck, 2005). Difference waveforms are also problematic in that they may produce artificial peaks if onset and offset latencies or component latencies in original waveforms differ across conditions. This is particularly the case when creating difference waveforms from correct and incorrect responses where there may be considerable discrepancies in reaction time (Falkenstein et al, 1990; Christ et al., 2000). Although it is clear that difference waveforms are limited in their capacity to uncover components accurately, this method which is in use in ERN/Ne research should therefore be considered carefully.

Given the differing approaches to ERP quantification and the various advantages and disadvantages noted, the aim of this research was to investigate three differing approaches to the quantification of ERN/Ne and evaluate the appropriateness of these in a language based task. The scoring methods evaluated were peak amplitude and latency measures, and analysis of mean amplitude. Both

these approaches were also applied to components identified within difference waveforms that were derived from the subtraction of correct response activity from error response activity where the number of trials for correct and incorrect responses was both matched and unmatched.

## **Method**

### **Participants**

Sixty one female, right-handed participants aged between 18 and 35 years, ( $M = 20.56$ ), were recruited from first year psychology students at the University of Tasmania and given course credit for their participation time. The study had ethical approval from the Human Research Ethics Committee (Tasmania) Network. Age restrictions were included due to noted decreases in ERP component amplitudes with increasing age (Friedman, Boltri, Vaughan, & Erlenmyer-Kimling, 1985).

Participants were screened according to a medical history questionnaire. Those with a history of mental or neurological disorders as well as those who were users of tobacco, cannabis, or prescription medication were excluded as these have been reported to affect ERP components (Polich & Kok, 1995). All participants reported normal or corrected to normal vision. Participants were grouped according to a median split of their decoding ability scores on the Martin and Pratt Nonword Reading Test (Martin & Pratt, 2001). Those participants with a raw score of 45 or below were considered poor decoders and those with a raw score of 46 or above were considered good decoders. Participants were also grouped in relation to their levels of conscientiousness as measured by a self-administered personality test, the Revised NEO Personality Inventory (NEO PI-R) (Costa & McCrae, 1992). Those with scores on the conscientiousness scale of this test ranging from zero to 31 were considered to have low levels of conscientiousness while those with scores of 32 and above were

considered to have high levels of conscientiousness. Data from participants were included for analysis providing 20 or more error responses were made in each experimental condition. Data from 23 participants were excluded because an insufficient number of error responses were made, leaving 38 participants with a mean age of 19.84 years whose data were included in analyses.

### **Apparatus**

The tasks were completed using Neuroscan Stim 3.1 software on a PC.

Electroencephalographic (EEG) data were recorded using Neuroscan SCAN 4.3.1 software on a PC and a 32 channel Quickcap with Ag/AgCl electrodes.

### **ERP recording**

EEG data were recorded from six midline (Fz, FCz, Cz, CPz, Pz, Oz) and 24 homologous scalp positions from both hemispheres (Fp1/2, F3/4, F7/8, Ft7/8, FC3/4, C3/4, T7/8, Tp7/8, CP3/4, P3/4, P7/8, O1/2) using linked mastoids as the reference and an AFz ground. Impedances were maintained at 10k $\Omega$  or less. Data were sampled continuously at 1000Hz and amplified at 200Hz. Continuous data were corrected for electro-oculographic (EOG) activity and average waveforms were computed for a 1000 ms epoch commencing 100 ms prior to response onset. Epochs were low-pass filtered at 30Hz and baseline corrected using a 100 ms pre-response time window. Data were included in averages provided an erroneous response was made and amplitude within the identified epoch did not exceed  $\pm 150\mu\text{V}$ .

### **Stimuli**

Participants completed two tasks: an orthographic and a phonological decision task. Each task consisted of five blocks of 60 trials of paired letter strings presented in 40 pt Times New Roman, white font on a black background. The stimuli were

presented, in pairs, on a computer screen for 1000 ms. They appeared randomly, left and right of centre with the word midpoint 3.5 cm from fixation. A fixation point was presented prior to the onset of each stimulus pair. The orthographic decision task comprised six-letter words paired with six-letter pseudohomophones (e.g., plaque, plarck). A full list is presented in Appendix A. Words used for this task occurred within a written frequency range of 1 to 100 per 100,000 (Kucera & Francis, 1967). The phonological decision task comprised six-letter pseudohomophones paired with six-letter pronounceable nonwords (e.g., whurce – whurne). A full list is presented in Appendix B. Each trial was preceded by a numerical cue (0, 20, and 100), indicating a points value associated with the following trial. This was presented in the centre of the screen for 2000 ms in 40 pt Times New Roman font. A response certainty screen followed each trial response with the question “Did you make an error?” appearing in the centre of the screen. The participant had four response options: no - very sure; no - somewhat sure; yes - somewhat sure; yes - very sure.

## **Procedure**

Participants attended the Cognitive Psychophysiology Laboratory for a session totalling approximately three hours. Initially, they completed the Medical screening questionnaire and The Edinburgh Inventory (Oldfield, 1971) to assess handedness. Participants then completed the Martin and Pratt Nonword Reading Test (Martin & Pratt, 2001), and a self administered personality test, the NEO PI-R (Costa & McCrae, 1992). Participants were then fitted with an electrode cap and completed the two computer-administered, counterbalanced tasks in a sound attenuated room. Each task was explained and opportunity for practice given before presentation. The cued points’ value (0, 20, and 100) for each trial was explained, along with disclosing information that a prize of \$50 would be awarded to the participant who accrued the

highest points score. The orthographic decision task required the participant to decide which word in the presented pair was a real word and respond appropriately by button press (left or right). The process was similar for the phonological decision task except participants were required to decide which word of the presented pair sounded like a real word. After completing each trial participants were asked to indicate whether their response was incorrect and how certain of this they were by appropriate button press. Participants were instructed to respond as quickly and accurately as possible. Rest periods followed each block of trials to prevent fatigue.

### **Design**

The experiment followed a 2 [Conscientiousness Level: low, high]  $\times$  2 [Decoding Ability: poor, good]  $\times$  2 (Trial Type: orthographic decision, phonological decision)  $\times$  3 (Task Salience: low, moderate, high)  $\times$  3 (Sagittal Site: frontal, fronto-central, central) mixed design. The ERP dependent measures were ERN/Ne amplitude and latency for each of the areas of comparison; peak detection, mean amplitude measures, and difference waveforms.

### **Analysis**

The analysis was limited to data associated with the phonological decision task because there were inadequate numbers of error responses to the orthographic decision task to enable inclusion of this response data. The average numbers of errors made during the orthographic task for the low, moderate and high task salient conditions were 4.93, 7.00 and 4.22 respectively. Analysis of ERN/Ne data was confined to frontal, fronto-central and central midline sagittal regions as ERN/Ne has been found to be maximal at these sites (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Falkenstein et al., 2000; Gehring, Goss, Coles, Meyer, & Donchin,

1993; Yeung, Botvinick, & Cohen, 2004). Data were analysed for main effects and interactions for ERN/Ne amplitude and latency components derived from the peak detection method and mean amplitude and 50% area latency for components derived from mean amplitude measures. Data were also analysed for components derived from two types of difference waves using both of these approaches. In the first instance components were quantified within difference waves where trial numbers included in averages of correct and error responses were not equal, and secondly where trial numbers included in averages were equal. In each case, a four-way mixed measures ANOVA was used. Conscientiousness Level and Decoding Ability were between groups factors and Task Salience, and Sagittal Region (Fz, FCz, Cz) were repeated measures factors. All significance levels were maintained at  $p < .05$ , following Huynh-Feldt corrections. Significant interactions were followed up with Tukey HSD post hoc tests where appropriate.

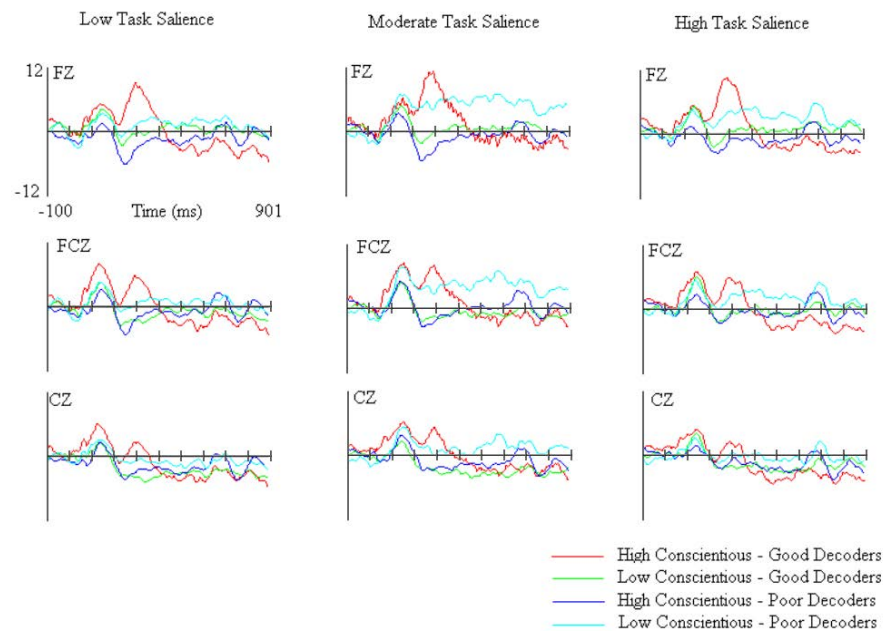
## **Results**

### **Peak Detection**

#### **Grand mean averages.**

Perusal of grand mean averages confirmed that ERN/Ne was maximal at frontal, fronto-central and central sagittal sites (see Figure 1) and is also similar to the findings of other researchers (see Falkenstein et al., 1991; Falkenstein, Hoormann, Christ, & Hohnsbein, 2000, Gehring, Goss, Coles, Meyer, & Donchin, 1993; Yeung et al., 2004). Figure 1 shows the grand mean averages for high and low conscientious, good and poor decoders across three task salience conditions (low, moderate, and high) at midline sites. As can be seen in the figure, ERN/Ne amplitude is maximal at frontal and fronto-central sites and the peak occurs approximately 50 ms post response. This guided the choice of the epoch from which peaks were picked

and from where mean amplitude and 50% area latency were measured (0 to 100 ms post response). This time frame is also in concordance with some past research in the area (Hajcak, Moser et al., 2005, Hajcak et al, 2004; Hajcak & Simons, 2008), however other researchers have chosen a range of differing measurement windows, for example 25 ms pre-response to 175 ms post response (Pailing & Segalowitz, 2004) and 50 ms pre-response to 150 ms post response (Compton et al., 2007). For this experiment, on the basis of the grand means, the ERN/Ne peak was defined as the most negative amplitude point within the 0 - 100 ms post response time window.



*Figure 1.* Grand mean average waveforms for high and low conscientious, good and poor decoders completing a low (left panel), moderate (middle panel) and high (right panel) task salience condition.

The grand mean average amplitudes range between approximately 0 and -5  $\mu$ V. This is somewhat lower than that reported by researchers in the field (e.g., Falkenstein et al., 2000; Hajcak et al., 2005), although ERN/Ne amplitude has been shown to vary according to experimental condition. Falkenstein et al., (2000) have demonstrated

ERN/Ne amplitude to be larger in four-way choice reaction tasks than amplitudes elicited during an Eriksen task. Similarly, it has been found that ERN/Ne amplitudes elicited during visual tasks are larger than those elicited during auditory tasks (Leuthold & Sommer, 1999).

### **ERN/Ne peak amplitude.**

Data for ERN/Ne peak amplitude were analysed using a 2 [Decoding Ability: poor, good]  $\times$  2 [Conscientiousness Level: low, high]  $\times$  3 (Task Salience: low, moderate, high)  $\times$  3 (Sagittal Site: Fz, FCz, Cz) mixed four-way ANOVA. A significant main effect of Sagittal Site,  $F(2, 68) = 11.69$ ,  $MSE = 1.88$ ,  $p < .001$ ,  $\epsilon = 0.92$ , was found.

Tukey post hoc tests revealed that ERN/Ne peak amplitude was significantly larger at Fz ( $M = -2.47$ ,  $SE = 0.36$ ) and FCz ( $M = -2.35$ ,  $SE = 0.38$ ) compared to Cz ( $M = -1.61$ ,  $SE = 0.40$ ) ( $ps < .05$ ). ERN/Ne peak amplitude at Fz was not significantly different than that at FCz. No further significant main effects or interactions were evident.

### **ERN/Ne peak latency.**

Data for ERN/Ne peak latency were analysed using a 2 [Decoding Ability]  $\times$  2 [Conscientiousness Level]  $\times$  3 (Task Salience)  $\times$  3 (Sagittal Site) mixed four-way ANOVA. A significant Decoding Ability  $\times$  Conscientiousness Level interaction was found,  $F(1, 34) = 7.19$ ,  $MSE = 1612.5$ ,  $p = .01$ , (see Figure 2). Although no individual comparisons reached significance, following Tukey post hoc tests, it can be clearly seen in Figure 2 that high conscientious poor decoders showed a longer ERN/Ne peak latency than high conscientious good decoders; whereas low conscientious poor decoders showed a shorter ERN/Ne peak latency than low conscientious good decoders.



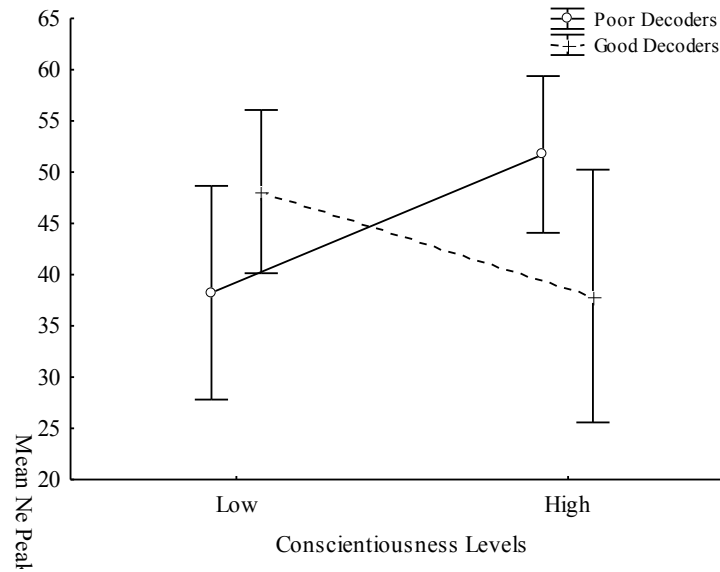


Figure 2. Mean ERN/Ne peak latency (ms) for low and high conscientious good and poor decoders (vertical lines represent 95% confidence intervals).

## Mean Amplitude

### ERN/Ne mean amplitude.

Data for ERN/Ne mean amplitude were analysed using a 2 [Decoding Ability]  $\times$  2 [Conscientiousness Level]  $\times$  3 (Task Saliency)  $\times$  3 (Sagittal Site) mixed four-way ANOVA. ERN/Ne mean amplitude was significantly larger for high conscientious participants ( $M = 3.89$ ,  $SE = 0.45$ ) than low conscientious participants ( $M = 2.45$ ,  $SE = 0.44$ ),  $F(1, 34) = 5.21$ ,  $MSE = 30.46$ ,  $p = .03$ . A trend approaching significance was evident for a Task Saliency  $\times$  Sagittal Site interaction,  $F(4, 136) = 3.36$ ,  $MSE = 1.06$ ,  $p = .05$ ,  $\epsilon = 0.43$ , and a trend towards a significant Task Saliency  $\times$  Sagittal Site  $\times$  Conscientiousness Level interaction,  $F(4, 136) = 3.05$ ,  $MSE = 1.06$ ,  $p = .07$ ,  $\epsilon = 0.43$ , was also apparent. These effects were all modified by a higher order significant Task Saliency  $\times$  Sagittal Site  $\times$  Decoding Ability  $\times$  Conscientiousness Level interaction,  $F(4, 136) = 4.54$ ,  $MSE = 1.06$ ,  $p = .02$ ,  $\epsilon = 0.43$  (see Figure 3). Breakdown ANOVAs

conducted at each sagittal level revealed a significant three-way interaction at FCz,  $F(2, 68) = 3.57$ ,  $MSE = 1.39$ ,  $p = .03$ ,  $\epsilon = 1$ , and a trend approaching significance at Fz,  $F(2, 68) = 3.21$ ,  $MSE = 3.52$ ,  $p = .05$ ,  $\epsilon = 0.90$ , but not at Cz,  $F(2, 68) = 2.09$ ,  $MSE = 1.04$ ,  $p = .13$ ,  $\epsilon = 1$ , sites. However, further post hoc analysis did not reveal any significant differences at FCz. As can be seen in Figures 3a and 3b very little difference in ERN/Ne mean amplitude is apparent across Decoding Ability, Conscientiousness Levels and Task Salience at fronto-central and central sites. At the Fz, Tukey post hoc analysis revealed that there were no significant differences in mean ERN/Ne amplitude between high and low conscientious poor decoders or between low conscientious good and poor decoders across low, moderate and high task salience conditions. However, low conscientious good decoders showed significantly larger mean ERN/Ne amplitude compared to high conscientious good decoders. Also high conscientious, poor decoders showed significantly larger mean ERN/Ne amplitude compared to high conscientious, good decoders ( $p < .05$ ).

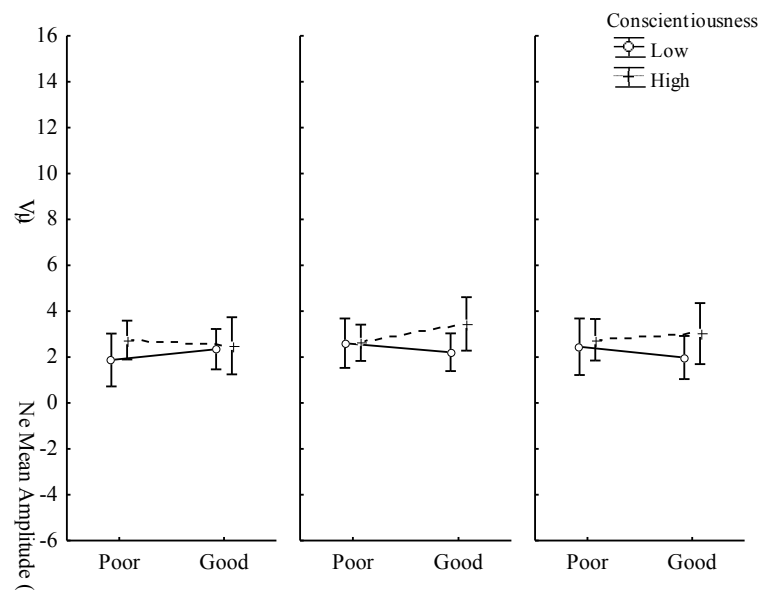
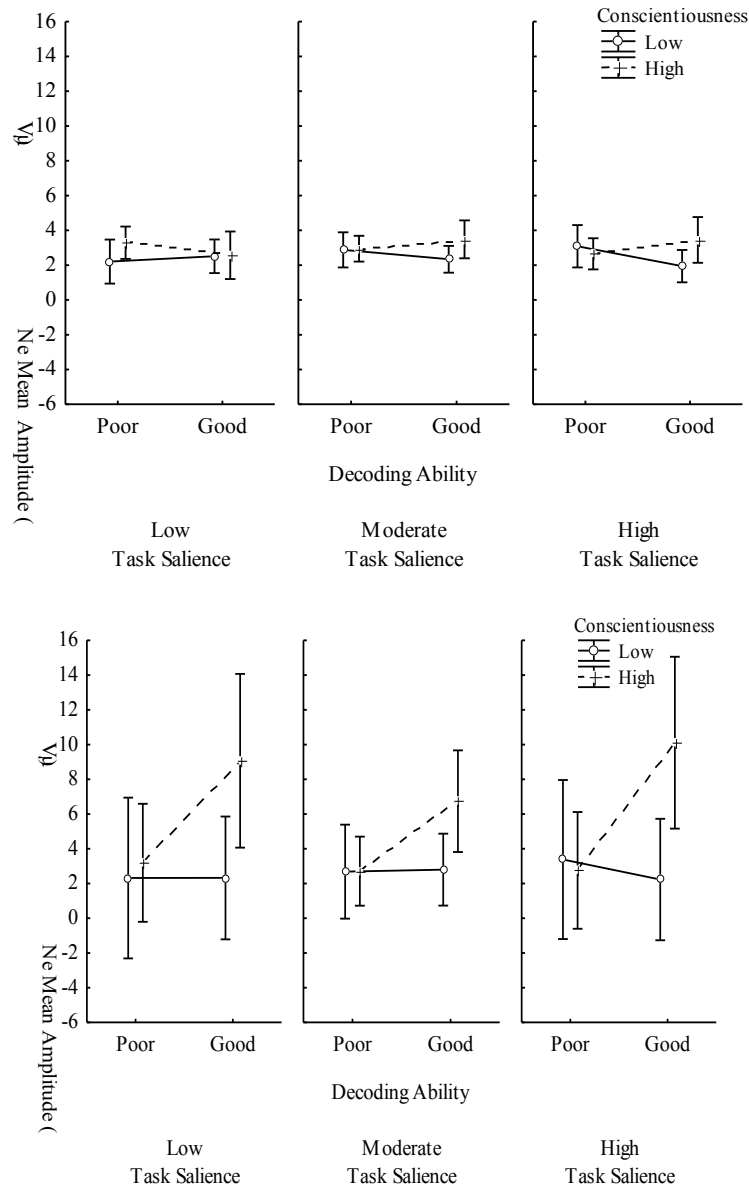


Figure 3a. ERN/Ne mean amplitude ( $\mu V$ ) for low and high conscientious, poor and good decoders across task salience conditions at Cz.

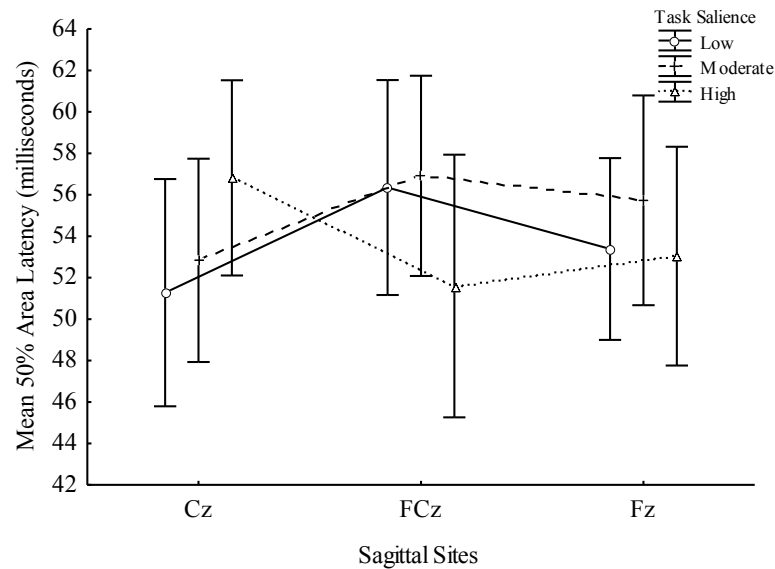


*Figure 3b.* ERN/Ne mean amplitude ( $\mu\text{V}$ ) for low and high conscientious, poor and good decoders across task salience conditions at FCz (middle panel) and Fz (bottom panel) (vertical lines represent 95% confidence intervals).

#### **ERN/Ne 50% area latency.**

Data for ERN/Ne 50% area latency were analysed using a 2 [Decoding Ability]  $\times$  2 [Conscientiousness Level]  $\times$  3 (Task Salience)  $\times$  3 (Sagittal Site) mixed four-way ANOVA. Mean 50% area latency was significantly larger for good decoders ( $M = 57.34$ ,  $SE = 2.21$ ) than poor decoders ( $M = 51.09$ ,  $SE = 2.07$ ),  $F(1, 34) = 4.27$ ,  $MSE$

= 702,  $p=.04$ . The Task Salience  $\times$  Sagittal Site interaction was also significant,  $F(4, 136) = 3.73$ ,  $MSE = 76.8$ ,  $p=.007$ ,  $\epsilon = 0.97$ . While Tukey post hoc tests did not reveal any further significant differences, Figure 4 shows that the significant interaction is a result of the difference in high task salient conditions compared to moderate and low task salient conditions at FCz and Cz



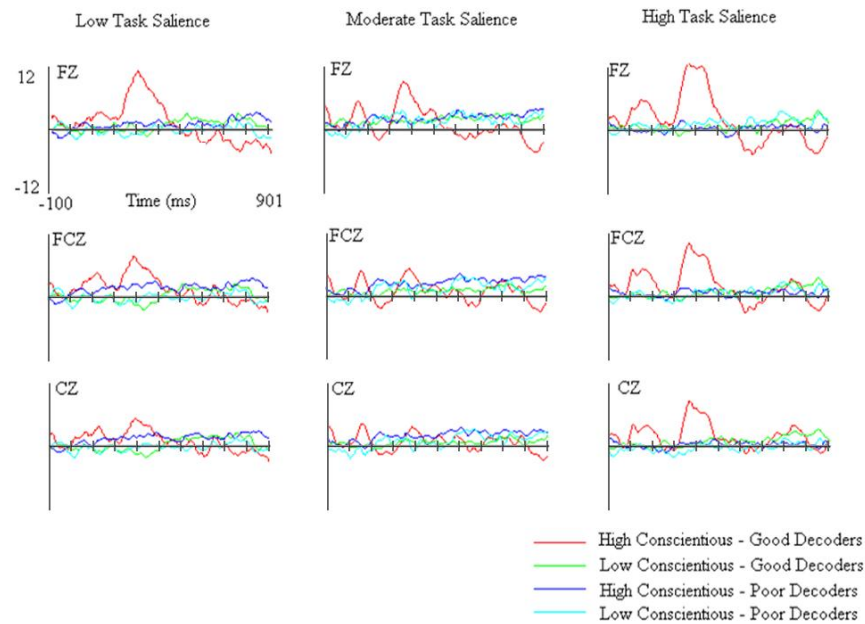
*Figure 4.* Mean 50% area latency (milliseconds) for low, moderate and high task salience conditions at Cz, FCz and Fz (vertical lines 95% confidence intervals).

### **Difference Wave Forms (Unmatched Trial Numbers)**

#### **Grand mean averages.**

Difference wave forms were computed by subtracting averaged error responses from averaged correct responses for three midline sites (Fz, FCz, and Cz) and are presented in Figure 5. Trial numbers included in these averages were unmatched. The number of trials included in error response averages ranged from 20 to 56. The number of trials included in correct response averages ranged from 22 to 83. The grand mean waveforms for the high conscientious good decoder group, ( $n = 6$ )

revealed considerable noise. Consequently, for the purpose of illustration, the waveforms for this group were smoothed.



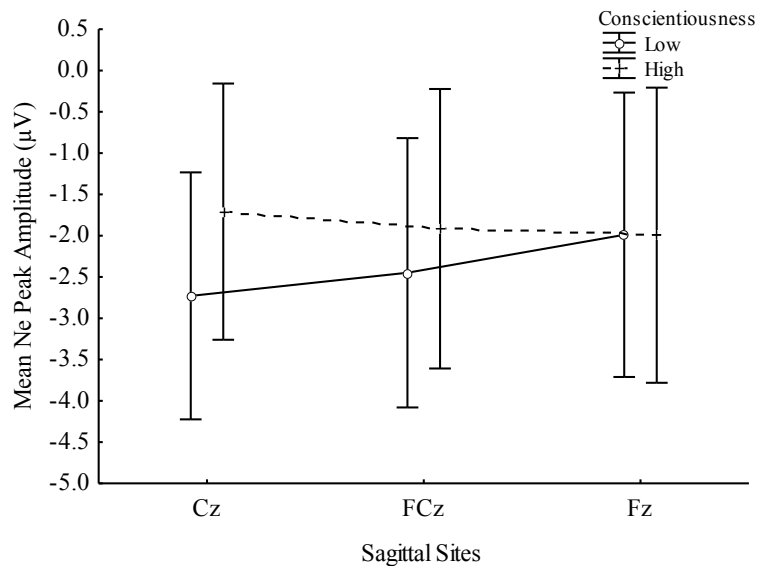
*Figure 5.* Grand mean average difference waveforms (unmatched trial numbers) for high and low conscientious, good and poor decoders in a low (left panel) moderate (middle panel) and high (right panel) task salience conditions.

As can be seen in Figure 5, grand mean averages of difference wave forms did not show a clear peak in the 0 -100 ms post response time window with the exception of the high conscientious good decoder group.

### **ERN/Ne peak amplitude.**

Data for ERN/Ne peak amplitude, derived from unmatched trial difference waves, were analysed using a 2 [Decoding Ability]  $\times$  2 [Conscientiousness Level]  $\times$  3 (Task Salience)  $\times$  3 (Sagittal Site) mixed four-way ANOVA. No significant main effects or interactions were found, however a trend approaching significance was evident for a Sagittal Site  $\times$  Conscientiousness Level interaction,  $F(2, 68) = 3.05$ ,  $MSE = 2.2$ ,  $p =$

.06,  $\epsilon = 0.93$ . Figure 6 indicates that low conscientious participants showed larger ERN/Ne peak amplitude than high conscientious participants at Cz and FCz but at Fz there was very little difference in ERN/Ne peak amplitude derived from unmatched difference waves.



*Figure 6.* ERN/Ne peak amplitude ( $\mu\text{V}$ ) for low and high conscientious participants at central, fronto-central and frontal sagittal sites (vertical lines represent 95% confidence intervals).

### **ERN/Ne peak latency.**

Data for ERN/Ne peak latency, derived from unmatched trial difference waves, were analysed using a 2 [Decoding Ability]  $\times$  2 [Conscientiousness Level]  $\times$  3 (Task Salience)  $\times$  3 (Sagittal Site) mixed four-way ANOVA. No significant main effects or interactions were found, however a trend approaching significance was evident for a main effect of Task Salience,  $F(2, 68) = 2.62$ ,  $MSE = 2807.6$ ,  $p = .07$ ,  $\epsilon = 1$ . There was little difference in ERN/Ne peak latency for low and moderate task salience conditions but high task salience conditions produced a considerably larger ERN/Ne peak latency.

### ERN/Ne mean amplitude.

ERN/Ne mean amplitude, derived from unmatched trial difference waves, was calculated as an average of rectified amplitude in the 0 - 100 ms post response time window. Data for difference wave mean ERN/Ne amplitude were analysed using a 2 [Decoding Ability]  $\times$  2 [Conscientiousness Level]  $\times$  3 (Task Salience)  $\times$  3 (Sagittal Site) mixed four-way ANOVA. A significant main effect of Conscientiousness Level,  $F(1, 34) = 6.34$ ,  $MSE = 58.54$ ,  $p = .02$ , and a significant main effect of Decoding Ability  $F(1, 34) = 4.13$ ,  $MSE = 58.54$ ,  $p = .04$ , were found. However, these were subsumed by a significant Conscientiousness Level  $\times$  Decoding Ability interaction,  $F(1, 34) = 4.28$ ,  $MSE = 58.54$ ,  $p = .04$ . As shown in Figure 7 and confirmed by Tukey post hoc tests, poor decoders showed no significant difference in difference wave mean ERN/Ne amplitude across conscientiousness levels however low conscientious, good decoders demonstrated significantly larger difference wave mean ERN/Ne amplitude than high conscientious, good decoders ( $p < .05$ ).

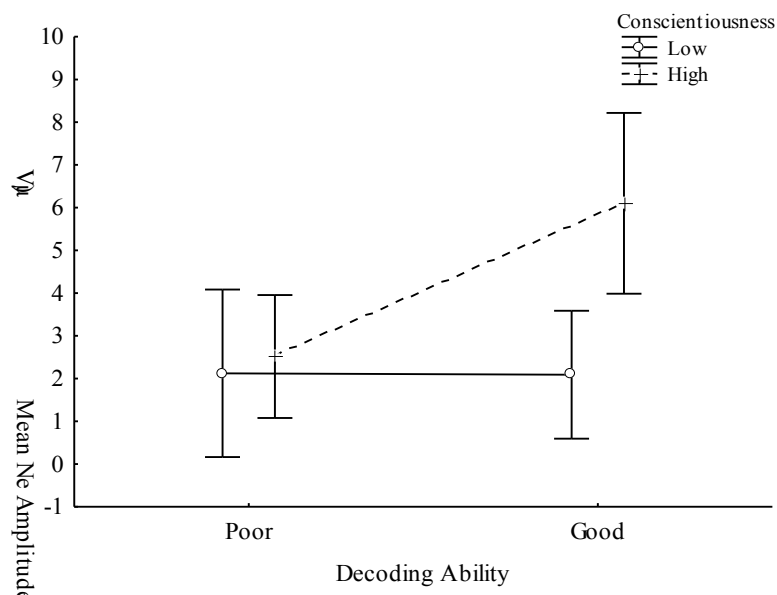


Figure 7. ERN/Ne mean amplitude ( $\mu V$ ) for high and low conscientious, good and poor decoders (vertical lines represent 95% confidence intervals).

No significant difference in difference wave mean ERN/Ne amplitude was evident for low conscientious participants across decoding abilities however, high conscientious, poor decoders showed significantly larger difference wave mean ERN/Ne amplitude compared to high conscientious, good decoders ( $p < .05$ ).

A significant main effect of Sagittal Site,  $F(2, 68) = 4.06$ ,  $MSE = 31.44$ ,  $p = .04$ ,  $\epsilon = 0.55$ , was also found, and while Tukey post hoc tests did not reveal any significant differences, examination of means indicate that difference wave mean ERN/Ne amplitude was more negative at Cz, ( $M = 2.36$ ,  $SE = 0.32$ ) and FCz, ( $M = 2.78$ ,  $SE = 0.37$ ) than at Fz, ( $M = 4.48$ ,  $SE = 0.97$ ).

A trend approaching significance was apparent for a main effect of Task Salience,  $F(2, 68) = 3.07$ ,  $MSE = 36.77$ ,  $p = .06$ ,  $\epsilon = 0.74$  which was modified by a higher order significant Task Salience  $\times$  Decoding Ability interaction,  $F(2, 68) = 4.00$ ,  $MSE = 36.77$ ,  $p = .03$ ,  $\epsilon = 0.66$  (see Figure 8).

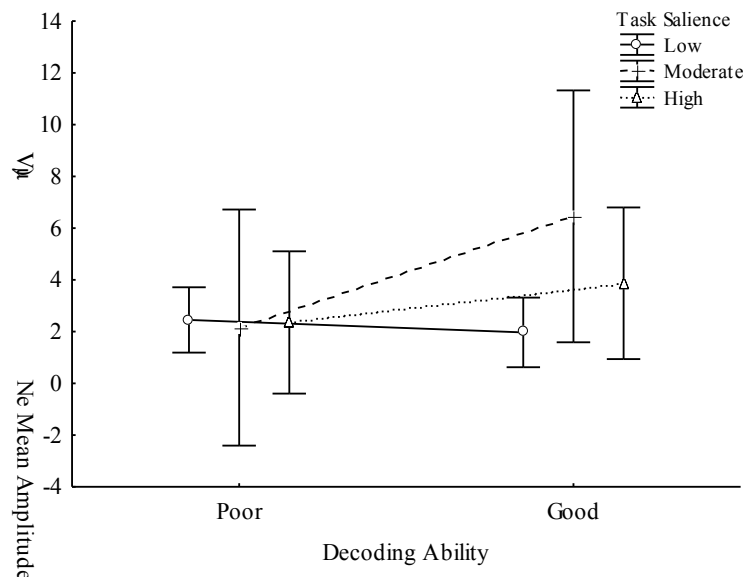
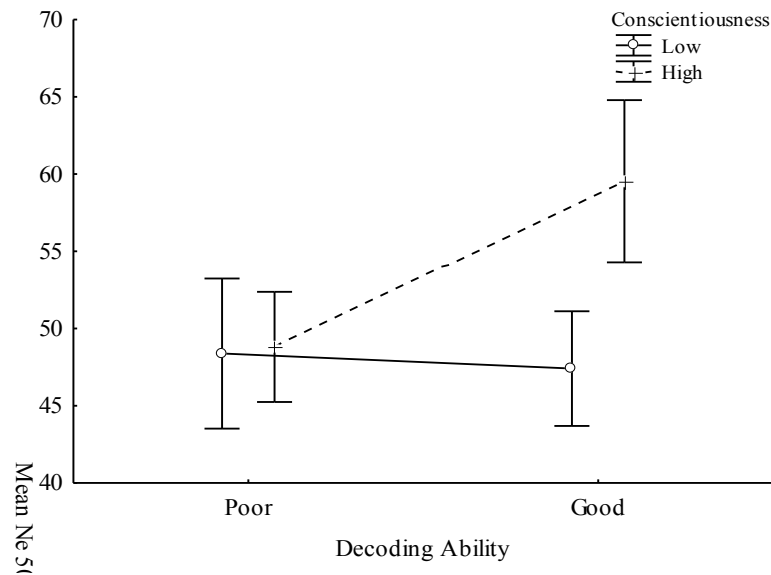


Figure 8. ERN/Ne mean amplitude ( $\mu V$ ) for good and poor decoders across low, moderate and high task salience conditions (vertical lines represent 95% confidence intervals).



As can be seen in Figure 8, and confirmed by Tukey post hoc tests, poor decoders showed no significant difference in difference wave mean ERN/Ne amplitude across task salience conditions ( $ps > .05$ ). However, good decoders showed significantly larger difference wave mean ERN/Ne amplitude in a low task salience condition compared to a moderate task salience condition ( $p < .05$ ). While no other comparison reached significance, it can be seen in Figure 9 that mean ERN/Ne amplitude for good decoders completing a high task salience condition was also higher than when completing the low task salience condition.



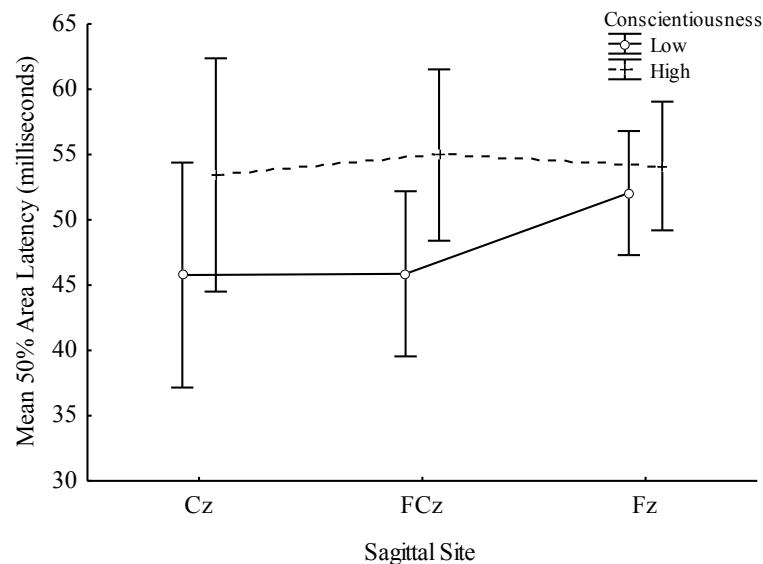
*Figure 9.* Mean ERN/Ne 50% area latency (milliseconds) for high and low conscientious good and poor decoders (vertical lines represent 95% confidence intervals).

#### **ERN/Ne 50% area latency.**

Data for ERN/Ne 50% area latency, derived from unmatched trial difference waves, were analysed using a 2 [Decoding Ability]  $\times$  2 [Conscientiousness Level]  $\times$  3 (Task Salience)  $\times$  3 (Sagittal Site) mixed four-way ANOVA. Significant main effects of Decoding Ability,  $F(1, 34) = 5.05$ ,  $MSE = 360.5$ ,  $p = .03$ , and Conscientiousness

Level,  $F(1, 34) = 8.38$ ,  $MSE = 360.5$ ,  $p = .006$ , were found. However, these effects were modified by a higher order Decoding Ability  $\times$  Conscientiousness Level interaction,  $F(1, 34) = 7.27$ ,  $MSE = 360.5$ ,  $p = .01$ . As shown in Figure 9 and confirmed by Tukey post hoc tests high conscientious good decoders showed significantly greater 50% area latency than high conscientious poor decoders, low conscientious good decoders, and low conscientious poor decoders ( $ps < .05$ ). No other comparisons reached significance.

While a trend approaching significance was apparent for a main effect of Sagittal Site,  $F(2, 68) = 3.01$ ,  $MSE = 112.6$ ,  $p = .05$ ,  $\epsilon = 1$ , the higher order Sagittal Site  $\times$  Conscientiousness Level interaction was significant,  $F(2, 68) = 3.13$ ,  $MSE = 112.6$ ,  $p = .04$ ,  $\epsilon = 1$ . Tukey post hoc tests revealed that 50% area latency was significantly greater for low conscientious participants at Fz than at FCz and Cz ( $ps < .05$ ). This is illustrated in Figure 10. No other comparisons reached significance.

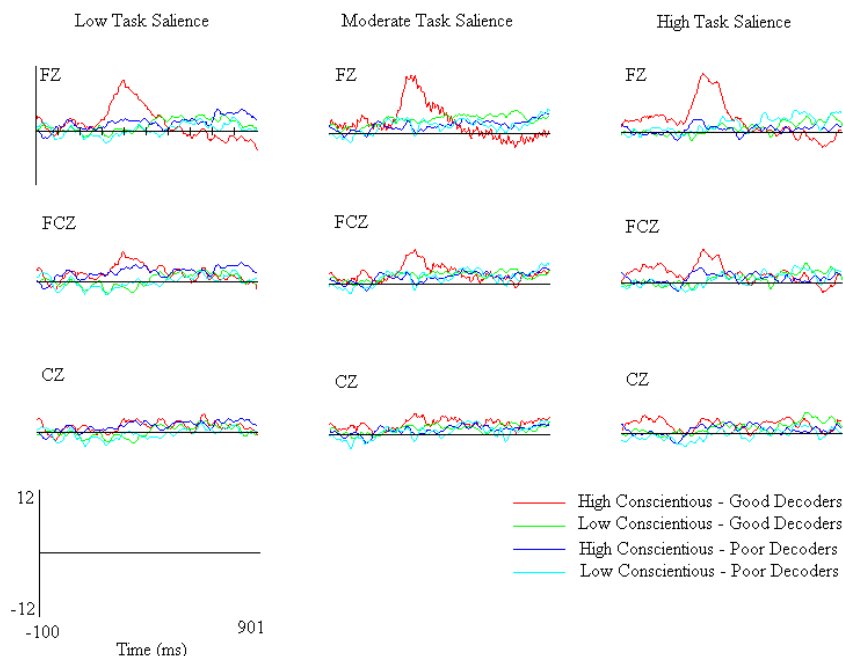


*Figure 10.* Mean 50% area latency (milliseconds) for low and high conscientiousness levels across Cz, FCz and Fz (vertical lines represent 95% confidence intervals).

## Difference Wave Forms (Matched Trial Numbers)

### Grand mean averages.

Difference wave forms were computed by subtracting averaged error responses from averaged correct responses for three midline sites (Fz, FCz, and Cz) and are presented in Figure 12. Error and correct response trial numbers included in these averages were matched for each participant across each experimental condition. As Figure 11 demonstrates grand mean averages of difference wave forms did not show a clear negative peak in the 0 -100 ms post response time window.



*Figure 11.* Grand mean average difference waveforms (matched trial numbers) for high and low conscientious, good and poor decoders in a low (left panel) moderate (middle panel) and high (right panel) task salience conditions.

### ERN/Ne peak amplitude.

Data for ERN/Ne peak amplitude, derived from matched trial difference waves, were analysed using a 2 [Decoding Ability]  $\times$  2 [Conscientiousness Level]  $\times$  3 (Task Salience)  $\times$  3 (Sagittal Site) mixed four-way ANOVA. No significant main effects or

interactions were evident for this analysis.

### ERN/Ne peak latency.

Data for ERN/Ne peak latency, derived from matched trial difference waves, were analysed using a 2 [Decoding Ability]  $\times$  2 [Conscientiousness Level]  $\times$  3 (Task Salience)  $\times$  3 (Sagittal Site) mixed four-way ANOVA. Mean ERN/Ne peak latency was significantly greater for high conscientious participants ( $M = 59.70$ ,  $SE = 4.97$ ) than low conscientious participants ( $M = 43.17$ ,  $SE = 4.79$ ),  $F(1, 34) = 0.02$ ,  $MSE = 3655.4$ ,  $p = .02$ . Also a trend approaching significance for a Task Salience  $\times$  Sagittal Site  $\times$  Conscientiousness Level interaction was found,  $F(4, 136) = 2.47$ ,  $p = .05$ ,  $\epsilon = 0.94$ . Figure 12 indicates that high conscientious participants showed little difference in mean ERN/Ne peak latency across task salience conditions and sagittal sites. However, low conscientious participants showed a general increase in mean ERN/Ne peak latency from low to high task salience conditions and little difference across sagittal sites.

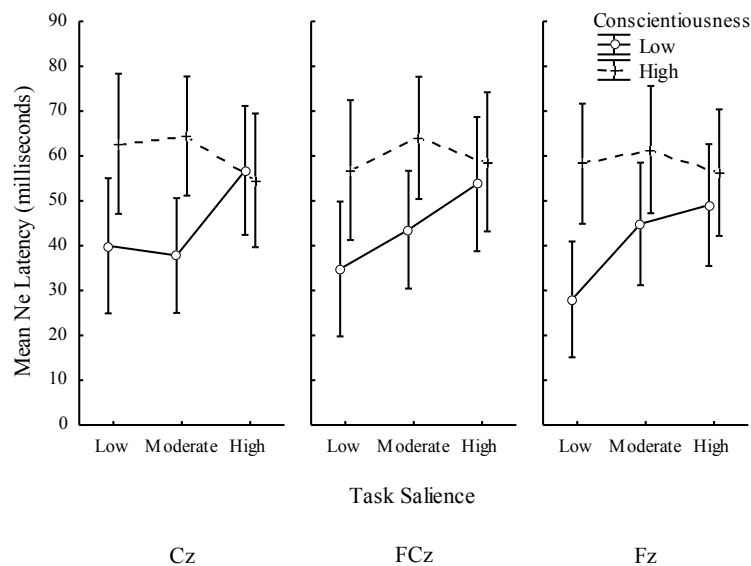


Figure 12. Mean ERN/Ne peak latency (milliseconds) for high and low conscientious participants across low moderate and high task salience conditions at Cz, FCz and Fz (vertical lines represent 95% confidence intervals).

### **ERN/Ne mean amplitude.**

Difference wave ERN/Ne mean amplitude (matched trial numbers) was calculated as an average of rectified amplitude in the 0 - 100 ms post response time window. Data for ERN/Ne mean amplitude derived from matched trial difference waves were analysed using a 2 [Decoding Ability]  $\times$  2 [Conscientiousness Level]  $\times$  3 (Task Salience)  $\times$  3 (Sagittal Site) mixed four-way ANOVA. A significant main effect of Sagittal Site  $F(2, 68) = 8.29$ ,  $MSE = 1.15$ ,  $p = .003$ ,  $\epsilon = 0.65$  was found. Tukey post hoc tests indicated that ERN/Ne mean amplitude was significantly greater at Fz, ( $M = 2.83$ ,  $SE = 0.27$ ) than Cz, ( $M = 2.24$ ,  $SE = 0.19$ ) ( $p < .05$ ), but not significantly different than mean amplitude at FCz ( $M = 2.54$ ,  $SE = 0.22$ ). Mean ERN/Ne amplitude at FCz was not significantly different from that at Cz.

### **ERN/Ne 50% area latency.**

Data for ERN/Ne 50% area latency, derived from matched trial difference waves, were analysed using a 2 [Decoding Ability]  $\times$  2 [Conscientiousness Level]  $\times$  3 (Task Salience)  $\times$  3 (Sagittal Site) mixed four-way ANOVA. A main effect of Conscientiousness Level was found,  $F(1, 34) = 4.65$ ,  $MSE = 446.8$ ,  $p = .04$ . However, this was subsumed by a significant higher order Task Salience  $\times$  Decoding Ability  $\times$  Conscientiousness Level interaction,  $F(2, 68) = 3.18$ ,  $MSE = 410.7$ ,  $p = .04$ ,  $\epsilon = 1$ . Whereas Tukey post hoc tests did not reveal any significant results, Figure 13 indicates similar differences between high and low conscientious poor and good decoders in low and high task salient conditions. In moderate task salience conditions, high conscientious good decoders recorded a considerably longer ERN/Ne 50% area latency than low conscientious good decoders.

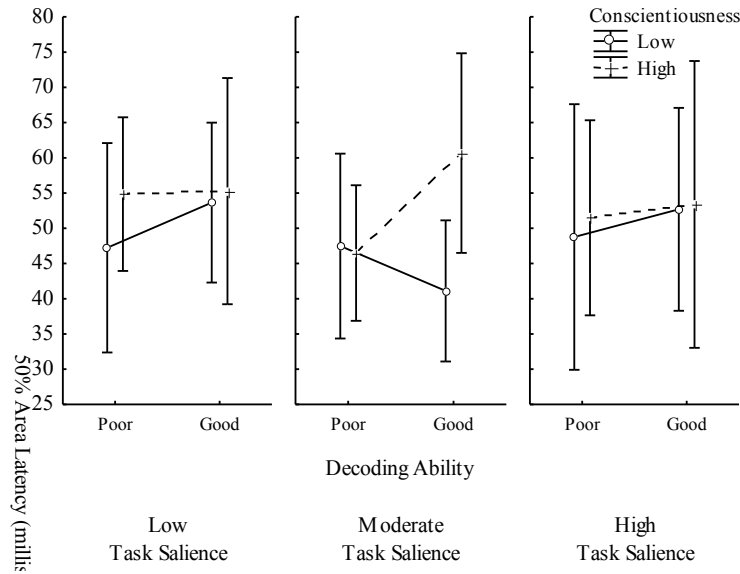


Figure 13. 50% area latency (milliseconds) for low and high conscientious, poor and good decoders across low, moderate and high task salience conditions (vertical lines represent 95% confidence intervals).

A significant Task Salience  $\times$  Sagittal Site  $\times$  Conscientiousness Level interaction was also found,  $F(4, 136) = 3.39$ ,  $MSE = 92.4$ ,  $p = .01$ ,  $\epsilon = 0.95$ . Breakdown analysis by sagittal site revealed a significant main effect of Task Salience at Cz,  $F(2, 72) = 5.42$ ,  $MSE = 184.2$ ,  $p = .006$ ,  $\epsilon = 1$ . Tukey post hoc tests indicated that 50% area latency was significantly greater for the low task ( $M = 55.26$ ,  $SE = 2.71$ ) salience condition than moderate ( $M = 45.08$ ,  $SE = 2.38$ ) but not high ( $M = 49.13$ ,  $SE = 2.44$ ) task salience conditions. There was no significant difference in 50% area latency between moderate and high task salience conditions. At FCz, breakdown analysis revealed a significant main effect of Conscientiousness Level,  $F(1, 36) = 6.24$ ,  $MSE = 185.3$ ,  $p = .01$ , such that participants with high conscientiousness levels ( $M = 53.56$ ,  $SE = 1.80$ ) showed significantly greater 50% area latency than participants with low conscientiousness levels ( $M = 47.19$ ,  $SE =$

1.80). No significant main effects or interactions were found at the frontal sagittal site.

The overall results are summarised in Table 1, and as can be seen there was no evidence of similar patterns of significance across the three general methods of quantification and within these methods there were differences in terms of significant outcomes.

Table 1. *Summary of main effects and interactions for each method of analysis.*

Main effects and interactions	Peak Detection and Mean Amplitude				Difference Waves (unmatched)				Difference Waves (matched)			
	Peak Amplitude	Peak Latency	Mean Amplitude	50% Area Latency	Peak Amplitude	Peak Latency	Mean Amplitude	50% Area Latency	Peak Amplitude	Peak Latency	Mean Amplitude	50% Area Latency
Decode				*			*	*				
Conscientiousness			*				*	**		*		*
Decode × Consc.		*					*	*				
Task Salience						$p=.06$	$p=.07$					
Task Salience × Decode							*					
Task Salience × Consc.												
Task Salience × Decode × Consc.												*
Sagittal	***						*	$p=.05$			*	
Sagittal × Decode							$p=.07$					
Sagittal × Consc.					$p=.06$			*				
Sagittal × Decode × Consc.												
Task Salience × Sagittal			$p=.06$	**								
Task Salience × Sagittal × Decode												
Task Salience × Sagittal × Consc.			$p=.07$							$p=.05$		*
Task Salience × Sagittal × Decode × Consc.			*									

\* -  $p<.05$  \*\* -  $p<.01$  \*\*\* -  $p<.001$ .



## Discussion

The aim of this study was to examine a number of approaches to the quantification of ERN/Ne within a language-based task. The current experimental data shows quite disparate outcomes within analyses of peaks, latencies, mean amplitude and 50% area latency (see Table 1), both across and within each quantification method.

Analysis of peak amplitude revealed a main effect of Sagittal Site such that activity was highest at frontal and fronto-central sites compared to activity at the central site and analysis of peak latency revealed a Decoding Ability x Conscientiousness Level interaction. However, when mean amplitude from the same averaged waveforms was analysed a quite different outcome emerged. Amplitude measures indicated a main effect of Conscientiousness that was modified by a four - way (Task Salience x Sagittal Site x Decoding Ability x Conscientiousness Level) interaction. Post hoc analysis indicated that there was very little difference in error negativity mean amplitude across experimental variables at both fronto-central and central sites. But in fact this interaction was driven by differences at Fz only. Fifty percent area latency analysis revealed a main effect of Decoding Ability, and also a difference in high task salient conditions compared to moderate and low task salient conditions at fronto-central and central sites resulted in a Task Salience x Sagittal Site interaction.

Considering peak detection and mean amplitude approaches to the quantification of error negativity, within this data set, two very different outcomes emerge. Peak amplitude measures indicate relevant activity spread across frontal and fronto-central sites( but no impact of the experimental variables) whereas mean amplitude measures indicated that the impact of the experimental variables only at Fz.

Again, when peak and mean amplitude and latency approaches were applied to difference waveforms derived from unmatched trial numbers for correct and incorrect responses, dissimilar findings were apparent. Using the peak detection method, no significant main effects or interactions for peak amplitude or latency were found. However, mean amplitude and 50 per cent area latency measures showed somewhat different patterns of significance. Mean amplitude measures revealed main effects of Decoding Ability and Conscientiousness Level that were modified by higher order interactions. Interestingly, a main effect of Sagittal Site revealed that error negativity was larger at central and fronto-central sites compared to the frontal site and this is inconsistent with the peak amplitude findings using the peak detection method where activity was highest at frontal sites.

The final analysis of peaks and means was based on difference waves derived from averages with matched trial numbers. For the peak detection method only a main effect of Conscientiousness Level was found for latency. Mean amplitude measures revealed a main effect of Sagittal Site such that activity was greatest at the frontal site compared to the central Sagittal Site, and a number of significant findings were evident when 50% area latency was analysed.

If the one similar finding that was evident across a number of methods is considered more closely, the main effect of Sagittal Site, again within these findings there were differences evident following post-hoc analysis. Peak amplitude analysis indicated that activity was focused at frontal and fronto-central areas. Mean amplitude measures derived from difference waves where averages included differing trial numbers showed activity more centrally and fronto-centrally located. Whereas, mean amplitude measures derived from difference waves where averages were matched in terms of trial numbers, showed that activity was focused frontally.

Thus, it can be clearly seen that, as Overbeek et al. (2005) indicated, differing methods of quantification can result in differing topographic presentations of activity.

Across each method of quantification of Ne, the predicted outcomes that high task value conditions would produce greater negativity than low task value conditions were generally not supported. When analysis of data quantified using a general mean amplitude method is examined, a number of interactions and trends approaching significance involving task salience are evident. However, these results were modified by other experimental variables; levels of conscientiousness and decoding ability levels. In fact, it was evident that conscientiousness levels only impacted ERN/Ne mean amplitude for good decoders. This occurred irrespective of task salience, with negativity greater for low conscientious than high conscientious participants. Considering the quantification of ERN/Ne using difference waves and subsequent mean amplitude analysis a two way interaction involving task salience and decoding ability levels was evident. No difference in mean ERN/Ne amplitude (unmatched trial difference waves) was shown across task salience conditions in poor decoders. However, for good decoders low task salient conditions produced greater mean ERN/Ne than moderate task salient conditions, but not high task salient conditions. No differences in mean ERN/Ne amplitude were evident when it was quantified using matched trial difference waves. Considering these outcomes it is clear that using different methods of quantification may result in contradictory outcomes. While the instance of experimental outcomes derived from unmatched trial difference waves is in some way supportive of the hypothesised outcomes, the other, contradictory outcomes derived from standard mean amplitude measures and

matched trial difference waves demonstrate the importance that a posteriori knowledge does not drive the choice of quantification.

It is evident that differing approaches to the quantification of ERP components are commonplace and, indeed, appropriate in many cases. Considering the disparate analysis outcomes in the current investigation of methods, a priori justification of the choice of component quantification is essential. Use of a peak detection method is appropriate when recognisable peaks are evident in grand mean averaged data. On the other hand, measures of mean amplitude can be used when both flat and peak morphologies are apparent. Difference waveforms, while controlling for any activity that is constant across conditions, often produce false or inaccurate peaks and should be used with caution. With these points mind, and the fact that a language-based experimental paradigm has not been used to investigate erroneous responses in the past, the most appropriate choice of method of quantification for ERN/Ne for the current experiment is mean amplitude and 50% area latency.

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## **APPENDIX B**

### **Medical and History Questionnaire**

## ERPs as Indices of Error Salience

### Medical and History Questionnaire

University of Tasmania

School of Psychology

Date...../...../.....

Participant Code.....

#### Medical History

Are you currently suffering from anxiety or depression? .....

Do you have a heart condition or any other serious physical condition?

.....

Are you currently taking any prescription medication? If so, what medication?

.....

.....

Have in the past taken any medications for psychological condition(s)? If so, what medications?

.....

.....

Is there any possibility that you could be pregnant?

.....

.....

Have you ever had or are you now suffering from any of the following (please circle):

Fits or convulsions	Yes	No
Epilepsy	Yes	No
Giddiness	Yes	No
Concussion	Yes	No
Severe Head Injury	Yes	No
Loss of Consciousness	Yes	No

### *Drinking and Smoking History*

On how many days last week did you drink alcohol?	None One or two days Three or four days Five or six days Every day	
Do you usually drink alcohol?	Never During weekdays Friday night Weekends	
How many drinks would you usually have at one time?	One or two Three to five Five to eight Eight to twelve More than twelve	
Do you get drunk?	Never Rarely Once a month Once a week	
How often do you smoke a cigarette?	Never Less than 5 per week Less than 5 per day 5 to 9 per day 10 to 19 per day 20 to 39 per day Over 40 per day	
Do you or have you in the past used marijuana? (Please circle)	Yes	No
a) Have you used marijuana in the last two weeks?	Yes	No
b) Have you used any other form of illicit drug in the last 6 months?	Yes	No

## **Vision**

Do you have any difficulties with vision? (Please specify)

.....

If yes, are these difficulties corrected (i.e. glasses/contacts)

.....

## **Reading**

Have you ever been diagnosed as reading disabled?	Yes	No
---	-----	----

Have you ever taken part in remedial education programs?	Yes	No
--	-----	----

Thank you for your participation

## **APPENDIX C**

### **Orthographic Decision Task – Word Pairs**

### Orthographic Decision Task – 6 Letter Word Pairs

leesed	leased	scwibb	squibb	wawned	warned
cloars	clause	thawns	thorns	spysed	spiced
chieze	cheese	druncs	drunks	thurst	thirst
plarck	plaque	healde	healed	quawtz	quartz
spylls	spills	sneeks	sneaks	greits	greet
karved	carved	thighz	thighs	roalde	rolled
countz	counts	luimed	loomed	sperns	spurns
sypped	sipped	lophed	loafed	chanes	chains
sckifs	skiffs	brycks	bricks	treups	troops
clymb	climbs	knytes	nights	scwirt	squirt
synged	singed	nerses	nurses	shaid	shades
bommed	bombed	goasts	ghosts	feered	feared
maugue	morgue	breafs	briefs	klaims	claims
showts	shouts	croame	chrome	shaips	shapes
creace	crease	credes	creeds	wrored	roared
fauced	forced	streac	streak	pirged	purged
irgned	earned	transe	trance	preech	preach
haudds	hordes	leared	leered	staike	steaks
srybe	scribe	fraizz	phrase	sleive	sleeve
tenced	tensed	psaild	sailed	kaupps	corpse
juises	juices	kraish	crèche	sparce	sparse
flokks	flocks	woonds	wounds	stakks	stacks
flycks	flicks	blumes	blooms	weeves	weaves
stincy	stinky	shoars	shores	weeles	wheels
wheand	weaned	phrade	frayed	takke	tacked
firled	furled	wreeth	wreath	lurgns	learns
soarde	soared	krowds	crowds	rheuts	routes
brede	breeds	sckils	skills	sweeds	swedes
flornt	flaunt	nikked	nicked	tukked	tucked
cheefs	chiefs	blancs	blanks	skoard	scored
strors	straws	feests	feasts	glanse	glance
clarcs	clerks	fletes	fleets	bumppte	bumped
klawed	clawed	poared	poured	pegged	penned
chycks	chicks	screan	screen	kerves	curves
breezz	breeze	stiphs	stiffs	squeke	squeak
hartes	hearts	harves	halves	storze	stores
cleers	clears	kursed	cursed	skwod	squads
grenes	greens	thaudd	thawed	gloadd	glowed
scaird	scared	coamed	combed	krunch	crunch
cortes	courts	braiks	brakes	staums	storms
skwork	squawk	kurved	curved	cwench	quench
granes	grains	skores	scores	rheped	reaped

preuns	prunes	spryte	sprite	bownds	bounds
dryfts	drifts	thwaut	thwart	shruded	shrewd
heeped	heaped	smoaks	smokes	gainde	gained
crooze	cruise	snales	snails	shreek	shriek
rokked	rocked	klowns	clowns	spruse	spruce
rippte	ripped	groavs	groves	fylmed	filmed
kwirks	quirks	brydge	bridge	rhytes	rights
seiled	sealed	florze	floors	stryng	string
nurves	nerves	flaiks	flakes	strole	stroll
stakte	staked	rhecks	wrecks	corzed	caused
snears	sneers	wreeld	reeled	koaxed	coaxed
drylls	drills	scirts	skirts	kooled	cooled
ciesed	seized	seuthe	soothe	gneivs	knives
viered	veered	kreacs	creeks	skotch	scotch
heuvvs	hooves	psighd	sighed	loande	loaned
troles	trolls	dyshe	dished	creaps	creeps
prikks	pricks	paynts	paints	heeves	heaves
klamps	clamps	frouns	frowns	twytch	twitch
fawlt	faults	bordes	boards	kworts	quarts
voalts	vaults	surves	serves	phande	fanned
whaudd	warred	tourte	taught	myffed	miffed
chaced	chased	wyshed	wished	phriet	fright
tiemed	teamed	sighnd	signed	sokked	socked
kraved	craved	phrils	frills	mailde	mailed
drynks	drinks	rakked	racked	kycked	kicked
kyssed	kissed	spauts	sports	sloade	slowed
weeves	weaves	beafed	beefed	clynch	clinch
psinde	sinned	foulde	fouled	kreics	creaks
praide	prayed	sleaps	sleeps	saudds	swords
pirsed	pursed	typed	tipped	spraiz	sprays
shorls	shawls	scunks	skunks	slooce	sluice
shakks	shacks	leened	leaned	douced	doused
crains	cranes	klique	clique	splean	spleen
snoadd	snowed	quenes	queens	shaics	shakes
fauned	fawned	klenes	cleans	deamed	deemed
ghards	guards	spouze	spouse	gleids	glides
quoats	quotes	stryfe	strife	stoans	stones
rhufed	roofed	croade	crowed	brudes	broods
dwaufs	dwarfs	shynes	shines	klumps	clumps
ghluvs	gloves	smakks	smacks	gnapte	napped
ghrece	grease	tempse	tempts	staics	stakes
teezed	teased	dounde	downed	swyngs	swings
plededs	pleads	cokced	cocked	trased	traced
grewve	groove	friese	freeze	draips	drapes



serged	surged	strydd	stride	truncs	trunks
ghydes	guides	dekked	decked	waumed	warmed
jeulls	jewels	klucks	clucks	noambs	gnomes
seenes	scenes	wawled	walled	shawts	shorts
pekked	pecked	mownds	mounds	preest	priest
cweint	quaint	skeem	scheme	ceesed	ceased
spased	spaced	krouns	crowns	throaz	throws
hurlde	hurled	skrypt	script	kloavs	cloves
lapced	lapsed	jumppte	jumped	dryves	drives
skreuz	screws	stokks	stocks	faught	fought
chooze	choose	grased	grazed	chawze	chores
highte	height	jailde	jailed	sertch	search
gnoard	gnawed	phrese	frieze	lynked	linked
squorl	squall	kauked	corked	speecs	speaks
wraind	rained	bagned	banned	nealls	kneels
minsed	minced	crymes	crimes	voised	voiced
swares	swears	theems	themes	gerked	jerked
pleazz	please	sweups	swoops		

### Orthographic Decision Task – Practice Trial Word Pairs

snorze	snores	porned	pawned	kleave	cleave
noarte	nought	stemes	steams	steaps	steeps
skrole	scroll	scwaus	squaws	shancs	shanks
cluncs	clunks	whurrs	whirrs	fleace	fleece
braizz	braise	whiphs	whiffs	stoaks	stokes
skwids	squids	koughs	coughs	clokes	cloaks
browze	browse	groaps	gropes	blymps	blimps
trauls	trawls	skalps	scalps	knoals	knolls
sleize	sleaze	nummed	numbed	shawed	shored
peevvs	peeves	wheaze	wheeze	skworm	squirm
flaidd	flayed	cuphed	cuffed	phuste	fussed
siethe	seethe	wrumed	roomed	kringe	cringe
souste	soused	fleuts	flutes	mylked	milked
koshed	coshed	cheets	cheats	klangs	clangs
staits	states	yirgns	yearns	jygged	jigged
psemed	seemed	scornz	scorns	shurks	shirks
cawlde	called	slupes	sloops	maunns	mourns
ternde	turned	flooks	flukes	craivs	craves
frende	friend	krypts	crypts	stears	steers
kricks	cricks	ruists	roosts	tredds	treads
terfed	turfed	quylts	quilts	psarms	psalms
wirked	worked	phleks	flecks	prouls	prowls
ceared	seared	smyths	smiths	krapes	crepes
grouce	grouse	mukked	mucked	scives	skives
sirved	served	yaunde	yawned	skonse	scones
dymmed	dimmed	scawch	scorch	slynks	slinks
grownd	ground	twerls	twirls	skruff	scruff
munths	months	spreez	sprees	sneazz	sneeze
huphed	huffed	flancs	flanks	werles	whirls
cwails	quails	smeers	smears	scophs	scoffs
snoozz	snooze	fluphs	fluffs	greeve	grieve
quophs	quaffs	ghylds	guilds	ploncs	plonks
streus	strews				

## **APPENDIX D**

### **Phonological Decision Task – Word Pairs**

### Phonological Decision Task – 6 Letter Word Pairs

krouns	krourp	swaidd	swaild	freizz	freish
wourks	brurks	phaumb	phaubb	rheech	rheest
treett	treend	whurce	whurne	loaphd	sloaph
skeams	queams	klauze	klaufs	farmbs	framth
ghoast	gloast	haitts	haiths	shautt	shaugg
glande	glang	phewds	pheund	discks	yiscks
kwirks	kwirt	frynge	frydds	skeame	skeabe
crewdd	thewdd	peeque	peegue	sckair	sckaid
phreec	phreet	space	spaint	loades	loadge
naimbs	naimth	toanes	toante	sheipp	sheigg
cripte	cripps	proovs	prools	frammb	fraint
plande	planct	corle	corme	growse	growds
screus	ghreus	krumms	krumps	ghlare	glarle
cround	crount	pakked	paksed	phaike	phaige
sauses	sausts	whoart	whorge	rheles	rhelph
feends	deends	gnawth	gnawls	wipped	wippth
shewte	shewlt	werkes	swerks	houzed	phouze
cheked	theked	krustt	krusps	skaile	skaims
drumbs	frumbs	kloann	gloand	loarze	loarle
ceetes	ceeths	wraind	shrain	rhowde	rhowch
grupes	gnupes	drownd	drowds	klycks	klycts
wawmed	tawmed	haulld	chauld	frawed	frawks
kloars	bloars	shairs	shaife	koarld	koarve
fawmed	gawmed	righze	brighz	quypce	quypht
hoarld	hoarbs	cinged	scinge	ghates	ghaths
pledged	pleved	ghrynd	ghrysp	gharde	gharpe
knokks	knokes	knames	knamth	treade	treage
giphed	giphth	strete	screte	sheegn	sheege
poacks	voacks	paidge	paides	sweett	sweent
whaugh	cwaugh	kapped	kappth	dighed	dights
ghapce	ghapte	lyncks	lynced	starvs	starth
foarte	foarch	baudds	baulds	sleide	sleind
cherch	chernt	twinze	twinte	whysck	whysts
scawed	scawlz	leunny	pleuny	psuitt	psuige
klouds	kloums	phlopp	phlond	scaile	scaipe
rhooms	rhooth	mighks	smighs	kreame	kreach
braude	brauce	spars	spargs	pseame	pseafe
rhench	rhencck	hyssed	byssed	bownd	bownte
chekks	chekts	kwoart	kwoach	wryscs	wrysed
fawlte	tawlte	claimn	claice	krainn	kraime
therds	therse	klotts	klotch	doutte	doutch

slighs	slighp	klikks	skilks	scynze	skynge
phined	phinte	gainns	gaints	poaced	spoace
plaind	plailt	wroadd	wroand	brounn	broonn
craule	crault	rhewls	rhewve	stroar	stroam
wrankz	crantz	ghoats	ghopes	skarze	skarth
peececs	speecs	gneiff	gneigg	caines	cainge
whaced	whache	psails	psaips	phaice	phaiph
treign	treives	wrodes	wrodge	staizz	staibe
coapes	coaphs	dropte	dropes	grynnd	brynnd
mowthe	mowtch	ghetts	ghetch	slopps	slophs
phreas	phreap	threds	thkert	taiped	staibe
stawks	stawgs	sckumb	sckung	puiled	puilds
wyphed	wyphth	psites	psitch	psinze	psinte
wrewph	wrewce	foaned	foants	smourl	smourp
traynd	traybs	starte	starlte	rhased	rhasks
phrede	phrete	dround	drouds	snayle	snayms
ghodds	ghodes	scwosh	scwoll	ruilse	crails
whercs	whervs	beuthe	beuths	ghrait	ghraib
meenns	meends	frynge	frynte	braynn	thrayn
skrips	skrift	larphs	clarph	mikced	dikced
thancs	thants	spekes	speked	senned	sennth
leavvs	spleav	bassed	dassed	courte	courbe
speack	speash	kloazz	kloabz	towgns	stowgn
phound	phounn	klarse	klarbs	nirves	snirve
knoart	knoarn	phaled	phalte	beenns	beents
rhaned	rhance	slepte	slepse	whairs	whaips
gneace	gneane	flicte	fliced	kounts	kounes
tusque	susque	theamn	theann	philed	philds
shuize	shuich	waiced	waiche	ghrean	ghreal
hintse	hinths	claime	claize	karrte	narrte
clykks	clycts	whirse	whirps	wraill	wraime
knowts	knowsh	torked	jorked	graipe	graimb
shirte	shirge	plaist	planst	rhaice	rhaimb
whawde	whawnt	bounse	bounge	tiethe	stiete
fludds	fludge	stryde	strysh	whunse	whunge
scrypt	scrynt	faulls	faulds	stowte	stowth
ghaimn	ghaish	whilde	whilge	fealed	fealts
trighz	trighm	smoack	smoast	shaime	shaind
slumbs	slumth	klowds	klowce	tighls	tighst
crumms	crumph	chinns	chinch	tikked	gikked
korles	korlts	phloat	phlobe	rhitch	rhiths
gnamed	gnamps	psirch	psirnt	vurbes	vurbed
knerce	knerms	fermes	fermth	kropce	krophs
kought	zought	farste	narste	bulque	bulced

gifts	ghifes	shaimn	shaibe	chorze	chorch
bloque	gloque	whaded	thaded	baiced	baiche
boosed	zoosed	traque	graque	hyntce	hynche
pails	pails	traign	traime	skoole	skoode
gneeds	gneeds	scaild	scaidd	shoart	shoarf
ghroaz	ghroam	stopce	topced	bloack	bloafs
whaun	whaunt	ceaced	ceache	mighn	mighbs
kleenn	kleede	pynque	bynque	sweate	sweale
shaime	shaild	scoop	sckoom	drincs	drings
thincs	thinch	phawm	phawch	floodd	floagg
phraud	phrauk	rhides	shides	knirce	knirge
lirgnt	lirged	daites	daiths	scwair	scwarr
skemes	skemms	gnirve	gnirbs	dentce	dentch
traiss	traiff	drighd	drighm	brunte	brunce
pholce	pholve	phawk	phawch	werste	jerste
kriess	kriebb	cawzed	dawzed	gnoune	gnoule

### Phonological Decision Task – Practice Trial Word Pairs

sckull	sckule	klanns	klanes	kaikes	skaike
phaked	phaved	streke	streen	stynks	stynds
breste	bresed	phleze	phleam	stroac	stroam
pauzed	lauzed	barths	tarthe	rhinse	rhinch
spooock	proock	jermbs	nermbe	haunns	haunth
ceeled	ceelds	throan	throap	dighns	dighps
moodes	moodge	rhaist	rhaigs	sckonz	sckont
jirked	dirked	trooce	trooms	ghlote	ghlope
sulcks	nulcks	wreede	wreend	koambs	koamth
sckand	sckang	scweaz	skweag	creese	creefs
thaute	thaups	slaide	slaime	fensed	gensed
coarce	woarce	ghreed	ghreem	stytych	stytes
phreec	phreet	crunes	crunge	jeapps	jeaphs
leache	feache	tripce	triph	shokte	shokts
spaist	spaish	heatts	heatch	moaped	moaths
hawcks	vawcks	beakes	heakes	praugn	prause
slapce	glapce	yourns	yourst	dighce	dighfs
shunze	shunck	clouns	cloust	kulled	julled
shipce	shipth	kloque	klonge	preuph	preutt
swetes	sweths	snacte	snache	wraque	draque
sherke	sherpe	chaice	chaint	blinck	blinch
sckunc	sckund	wrymed	wrymth	snawts	snawlt
kwilts	kwilms	tanque	vanque	maigns	maiggs
triste	trispe	greved	grevvs	shrinx	shrinz
shrynx	shrynt	flocte	floche	chypse	frypse

## **APPENDIX E**

### **Information Sheets**



## **Information Sheet (Experiments 1 and 2)**

### **ERPs as Indices of Error Salience**

Dr Frances Martin (Chief Investigator, Senior Lecturer, School of Psychology)  
Dr Andrea Adam (Investigator, Post Doctoral Fellow, Teaching and Learning)  
Andrea Carr (Student Investigator, School of Psychology)

Date:

We would like to invite you to participate in an experiment designed to investigate aspects of cognitive processing. These studies are being conducted as part of the requirements for a PhD in Psychology and will be carried out in the Cognitive Psychophysiology (ERP) Laboratory at the School of Psychology, University of Tasmania (Hobart). Dr Frances Martin can be contacted on 6226 2262 or e-mail: F.Martin@utas.edu.au; Dr Andrea Adam can be contacted on 6226 2188 or email: Andrea.Adam@utas.edu.au; Andrea Carr can be contacted at the ERP Laboratory on phone 6226 2885, or by email: arcarr@utas.edu.au.

If you decide to participate in this research you will gain experience in research procedures and also knowledge the cognitive processes associated with error responses. If you are enrolled in first year Psychology, you will also receive research participation credit for your participation. Although this research will not be applied to a special population or involve any type of therapeutic intervention, it will provide a foundation upon which we can have a better understanding of the mechanisms by which the cognitive information associated with errors is processed.

We are looking for female volunteers between the ages of 18 and 35. If you are a heavy tobacco or cannabis smoker, are a heavy alcohol drinker, have a history of, or are currently suffering from, a neurological condition, you should not volunteer for this study. I will ask you to complete a questionnaire about these conditions before the experiment begins. I will also ask you to complete a questionnaire measure of personality traits; the NEO-PI-R.

If you choose to volunteer for this research, you may be asked to come to the ERP laboratory for a two hour session in which you will be asked to complete simple cognitive tasks presented on a computer monitor. Prior to commencement of the study, you will be asked to sign a consent form which will evidence your agreement to participate. While you are performing some of these simple tasks your brain activity and the time it takes you to respond to the stimuli will be recorded. While the equipment used to measure brain activity may feel a little uncomfortable, it is not painful in any way, however if you have sensitive skin, you should inform the researcher. It is possible that you may get fatigued and to alleviate this, frequent rests will be given during the experimental sessions.

Your individual data will be treated confidentially. It will be kept in locked cabinets or on password secured computers at the School of Psychology at the University of

Tasmania for a period of at least five years (with the exception of the medical questionnaires which will be destroyed on completion of the study). Following completion of the research, the data will be published; however, no participant will be personally identifiable in these publications as only group data will be published. A summary of the results of these experiments will be available on the University of Tasmania School of Psychology Web page at [www.scieng.utas.edu.au/psychol](http://www.scieng.utas.edu.au/psychol) or will be available by contacting the researcher.

Participation in this research is entirely voluntary. You may choose to withdraw from the study at any time without prejudice. Deciding to withdraw from this research at any time will not affect your academic standing in any way. You can also choose at this time to withdraw any data previously collected. Participants will be given copies of this information sheet and the statement of informed consent. The researcher will be available after the testing session to answer any questions you may have. If you have any questions, or would like any additional information regarding this research please contact Dr Frances Martin on (03) 6226 2262, Dr Andrea Adam on (03) 6226 2188 or Andrea Carr on (03) 6226 7458.

This study has been approved by the Social Sciences Human Research Ethics Committee. If you have concerns or complaints about the conduct of this study should contact the Executive Officer of the HREC (Tasmania) Network on (03) 6226 7479 or email [human.ethics@utas.edu.au](mailto:human.ethics@utas.edu.au) The Executive Officer is the person nominated to receive complaints from research participants. You will need to quote [*HREC project number H8953*].

Dr Frances Martin  
(Chief Investigator)

Dr Andrea Adam  
(Investigator)

Andrea Carr  
(Student Investigator)

## **Information Sheet (Experiment 3)**

### **ERPs as Indices of Error Salience**

Dr Frances Martin (Chief Investigator, Senior Lecturer, School of Psychology)

Dr Andrea Adam (Investigator, Post Doctoral Fellow, School of Psychology)

Andrea Carr (Student Investigator, School of Psychology)

Date:

We would like to invite you to participate in an experiment designed to investigate aspects of cognitive processing occurring during word recognition tasks. These studies are being conducted as part of the requirements for a PhD in Psychology for Andrea Carr and will be carried out in the Cognitive Psychophysiology (ERP) Laboratory at the School of Psychology, University of Tasmania (Hobart). Dr Frances Martin can be contacted on 6226 2262 or e-mail: F.Martin@utas.edu.au; Dr Andrea Adam can be contacted on 6226 7519 or email: Andrea.Adam@utas.edu.au; Andrea Carr can be contacted at the ERP Laboratory on phone 6226 2885, or by email: arcarr@utas.edu.au.

If you decide to participate in this research you will gain experience in research procedures and also knowledge of the cognitive processes associated with error responses. If you are enrolled in first year Psychology, you will also receive research participation credit for your participation. Although this research will not be applied to a special population or involve any type of therapeutic intervention, it will provide a foundation upon which we can have a better understanding of the mechanisms by which the cognitive information associated with reading and with errors is processed.

We are looking for female volunteers between the ages of 18 and 35. If you are a heavy tobacco or cannabis smoker, are a heavy alcohol drinker, have a history of, or are currently suffering from, a neurological condition, you should not volunteer for this study. We will ask you to complete a questionnaire about these conditions before the experiment begins. We will also ask you to complete a questionnaire measure of personality traits; the NEO-FFI. We will also ask you to complete the Martin and Pratt Nonword Reading Test.

If you choose to volunteer for this research, you will be asked to come to the ERP laboratory for a three-hour session in which you will be asked to complete simple word recognition tasks presented on a computer monitor. Prior to commencement of the study, you will be asked to sign a consent form which will evidence your agreement to participate. While you are performing some of these simple tasks your brain activity and the time it takes you to respond to the stimuli will be recorded. While the equipment used to measure brain activity may feel a little uncomfortable, it is not painful in any way, however if you have sensitive skin, you should inform the researcher. It is possible that you may get fatigued and to alleviate this, frequent rests will be given during the experimental sessions.

Your individual data will be treated confidentially. It will be kept in locked cabinets or on password secured computers at the School of Psychology at the University of Tasmania for a period of at least five years (with the exception of the medical questionnaires which will be destroyed on completion of the study). Following completion of the research, the data will be published; however, no participant will be personally identifiable in these publications as only group data will be published. A summary of the results of these experiments will be available on the University of Tasmania School of Psychology Web page at [www.scieng.utas.edu.au/psychol](http://www.scieng.utas.edu.au/psychol) or will be available by contacting the researcher.

Participation in this research is entirely voluntary. You may choose to withdraw from the study at any time without prejudice. Deciding to withdraw from this research at any time will not affect your academic standing in any way. You can also choose at this time to withdraw any data previously collected. Participants will be given copies of this information sheet and the statement of informed consent. The researcher will be available after the testing session to answer any questions you may have. If you have any questions, or would like any additional information regarding this research please contact Dr Frances Martin on (03) 6226 2262, Dr Andrea Adam on (03) 6226 7519 or Andrea Carr on (03) 6226 7458.

This research has received ethical approval from the Human Research Ethics (Tasmania) Network. If you have any questions regarding the ethical nature or complaints about the manner in which the study is conducted, you may contact the Executive Officer (Amanda McAully on 03 6226 2763; email: [Human.ethics@utas.edu.au](mailto:Human.ethics@utas.edu.au) )

Dr Frances Martin  
(Chief Investigator)

Dr Andrea Adam  
(Investigator)

Andrea Carr  
(Student Investigator)

## **APPENDIX F**

### **Statement of Informed Consent**

## Statement of Informed Consent

### ERPs as Indices of Error Salience

Dr Frances Martin (Chief Investigator, Senior Lecturer, School of Psychology)

Dr Andrea Adam, (Investigator, Post Doctoral Fellow, School of Psychology)

Andrea Carr (Student Investigator, School of Psychology)

#### Participant Consent Statement:

I have read and understood the *Information Sheet* for this research. The nature and possible effects of the research have been explained to me. Any questions that I have asked have been answered to my satisfaction.

I understand that the research requires me to attend the ERP laboratory at the School of Psychology where my brain activity will be recorded while I am undertaking visual word recognition tasks. Setting up the experiment, completing pre-tests and task completion will take approximately three hours. I understand that I will be asked about recreational drug habits, use of prescription medication, and any neurological conditions. I also understand that a reading test will be administered and that I will be asked to complete one personality trait questionnaire. I understand that I should indicate to the experimenter if I have sensitive skin and that I should request a rest if I become fatigued.

I understand that all research data will be kept in locked cabinets or on password secured computers at the School of Psychology at the University of Tasmania for a period of at least five years (with the exception of the medical questionnaires which will be destroyed on completion of the study). I agree that research data gathered for the study may be published provided that I cannot be identified as a participant.

I agree to participate in the investigation and understand that I may withdraw from participation and/or withdraw my data at any time without prejudice to my academic standing.

Name of participant.....

Signature of participant..... Date.....

#### *Investigator Statement*

I have explained this research and the implications of participation in it to this volunteer and I believe that the consent is informed and that he/she understands the implications of participation.

Name of investigator.....

Signature of investigator..... Date.....

## **APPENDIX G**

### **Handedness Inventory**

## Handedness Inventory

For each of the activities below, please answer:

1. Which hand you prefer?
2. Do you ever use the other hand?

	Preferred hand		Ever use other hand?	
Writing	L	R	Y	N
Drawing	L	R	Y	N
Throwing	L	R	Y	N
Using scissors	L	R	Y	N
Using a toothbrush	L	R	Y	N
Using a knife (without a fork)	L	R	Y	N
Using a spoon	L	R	Y	N
Using a broom (upper hand)	L	R	Y	N
Striking a match	L	R	Y	N
Opening a box (lid)	L	R	Y	N

Do you ever confuse left and right?.....

How many people in your immediate family are left handed?.....



## **APPENDIX H**

### **Experimental Analyses (DVD)**

